UNIVERSITÉ DU QUÉBEC À MONTRÉAL

LES CHANGEMENTS PROJETÉS DES CARACTÉRISTIQUES DES INONDATIONS DANS UN CONTEXTE MULTI-VARIÉ SUR LA RÉGION DE QUÉBEC EN UTILISANT PLUSIEURS MRC DU PROJET NARCCAP

MÉMOIRE

PRÉSENTÉ

COMME EXIGENCE PARTIELLE

DE LA MAÎTRISE EN SCIENCES DE L'ATMOSPHÈRE

PAR

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FÉVRIER 2016

REMERCIEMENTS

Je tiens à remercier toutes les personnes qui ont contribué au succès de mon projet de recherche pour l'obtention de la maîtrise en sciences de l'atmosphère à l'UQÀM. Tout d'abord, j'adresse mes remerciements à ma professeure, **Dr. Laxmi Sushama** pour son encadrement et toute son équipe de recherche en particulier **Dr. Dae Il Jeong** qui m'a beaucoup aidé dans ma recherche.

Je tiens à remercier vivement ma femme Hadhemi Thlibi pour son soutien et sa patience durant mes études sans oublier mon bébé Mohamed Adam pour ses beaux sourires qui m'ont encouragé à atteindre mon objectif.

Je remercie également mes parents Nouredine et Saida, mon frère Marwan et ma sœur Marwa pour leurs soutiens malgrés les distances.

Enfin, je tiens à remercier tous les membres du centre ESCER pour leurs aides techniques et administratives.

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AOGCM	Atmospheric-Ocean General Circulation Model
CCSM	Community Climate System Model
CRCM	Canadian Regional Climate Model
CGCM3	Canadian Global Climate Mode! version 3
GCM	Global Climate Model
GEV	Generalized Extreme Value
GFDL	Geophysical Fluid Dynamics Laboratory
GIEC	Groupe d'experts Intergouvernemental sur l'Évolution du Climat
HadCM3	Hadley Centre Coupled Mode!, version 3
HRM3	Hadley Regional Mode! 3
IPCC	Intergovernemental Panel on Climate Change
MCG	Modèle de Circulation Générale
MCM	Million Cubic Meter
MRC	Modèle Régional du Climat
NCEP	National Center for Environmental Prediction
NARCCAP	North American Regional Climate Change Assessment Program
NCAO	National Center for Atmospheric Research
RCM	Regional Climate Model
SRES	Special Report on Emissions Scenarios
UQAM	Université du Québec à Montréal
WRFG	Weather Research & Forecasting

RÉSUMÉ

Dans cette étude, les impacts du changement climatique sur les caractéristiques des crues, c.-à-d le pic, le volume et la durée, sont évalués pour 21 bassins versants situés dans le Nord Est du Canada, couvrant principalement la province Québec. Plusieurs modeles régionaux climatiques (MRC) d'ensemble proveneant du North American Regional Climate Change Assessment Program (NARCCAP) sont utilisés. Trois MRC sont considérés, pilotés par les ré-analyses II de Nationale Center of Environemental Prediction (MRC-NCEP), pour la période 1980-2004, et par quatre modèles de circulation générale de l'atmosphère-océan (MRC-MCGA) pour le climat present étalant sur la pèriode de 1971 à 2000 et le climat future pour la pèriode 2041 - 2070. Une analyse de fréquence univariée pour chaque caractéristique d'inondation axée sur les niveaux de retour (5 et 30-ans) ainsi qu'une autre analyse bivariée dite copula basée sur les paires corrélés des caractéristiques des crues (c.-à-d pic-volume, pic-durée et volume-durée) sont effectuées. Les erreurs de performance des MRC provenant du parametrage dynamique et physique des modeles ainsi que les erreurs dues aux choix de forcage aux frontières par MCGA sont évaluées. En général, la performance de MRC-NCEP varie d'un modele à un autre et depend fortement de l'emplacement géographique des bassins visés. Les simulations MRC-MCGAs presentent des configurations spatiales differentes pour les erreurs dues au forçage aux frontières dans chaque étape d'analyse des caractéristiques des crues: analyse satistique, univariée et bi-variée. Ceci depend essentiellement du choix de modèle de circulation générale pour le pilotage. Les MRC-MCGA suggèrent une augmentation future dans les valeurs moyennes, dans les niveaux de retour de 5- et 30-ans et dans les probabilités conjointes d'occurrence des trois caractéristiques des crues, avec quelques diffeérences entre les bassins versants et entre les différentes simulations des combinaisons des modèles.

Mots clés: changement climatique, modélisation climatique régionale, Copula, caractéristiques des crues, analyse fréquentielle, Nord-Est Canadian.

ABSTRACT

In this study, climate change impacts on flood characteristics (i.e. peak, volume and duration) are evaluated for 21 northeast Canadian basins, covering mainly the Quebec province of Canada, based on a multi-Regional Climate Model (RCM) ensemble available through North American Regional Climate Change Assessment Program (NARCCAP). The set of simulations considered in this study includes simulations performed by three RCMs which are driven by National Centre for Environmental Prediction reanalysis II (RCM-NCEPs) for the 1980–2004 period and four Atmosphere-Ocean General Circulation Models (RCM-AOGCMs) for the current 1971–2000 and future 2041–2070 periods. The performance errors of RCMs due to internal dynamics and physics of the models are assessed by comparing streamflows generated from NCEP driven simulations with those observed on stations. A univariate frequency analysis of each flood characteristic corresponding to 5- and 30-yr return periods as well as Copula based bivariate frequency analyses for correlated pairs of flood characteristics (i.e. peak-volume, peak-duration and volume-duration) are evaluated and joined with the boundary forcing errors by comparing AOGCMs driven RCM simulations to those driven by NCEP. In general, the performance of RCM-NCEPs varies from one RCM to the other and strongly depends on the geographic location of each basin. All RCMs show different spatial behaviour of flood statistics and univariate and bivariate analyses which is due to the choice of the driving AOGCM. The analysis of RCM-AOGCMs for the future with respect to the current suggests an increase in the mean, marginal return levels and joint occurrence probabilities of flood characteristics with some differences noticed between basins, models and between different combinations of RCMs and AOGCMs.

Keywords: Climate change; regional climate modelling; copula; floods characteristics; frequency analysis; northeastern Canada;

CHAPITRE I

INTRODUCTION

Le changement climatique est un phénomène qui ne cesse de s'aggraver allumant le signal d'alerte par la communauté scientifique pour réagir et contrer ses effets sur la faune et la flore. En effet, le Groupe d'Experts Intergouvernemental sur l'Évolution du Climat (GIEC/IPCC), dans son cinquième rapport d'évaluation 2014, confirme ses inquiétudes concernant un réchauffement global, en cours et future, ce qui a affecté et affectera le cycle hydrologique. Le rapport prévoit une hausse de la moyenne globale de la température avec une augmentation de la précipitation en intensité et en fréquence. Ceci entraine une accélération de la fonte de la neige ce qui peut engendrer des crues au début de la saison du printemps.

Ces changements peuvent avoir des impacts sur la couverture neigeuse, dont une diminution est prévue, ce qui promouvoir la fonte de la neige, en particulier dans plusieurs régions de l'Amérique du Nord. Tout cela peut conduire à un ruissellement plus important qui s'intensifie au début du printemps, comme indiqué dans Hanna et al., 2008; Cao et al., 2010 et Gosling et al., 2011, en se basant sur des modèles hydrologiques à l'échelle globale aussi bien qu'à l'échelle du bassin. A son tour, le changement de ruissellement peut affecter d'une manière significative la dynamique des crues dans les bassins fluviaux du Canada là où les débits élevés sont essentiellement générés par la fonte nivale (Thiémonge et al., 2015). Tous ces changements, touchent sérieusement la société, conduisant à des énormes répercussions environnementales, sociales et politiques. Par exemple, Hydro-Québec a indiqué que 96% de l'énergie totale produite dans la province de Québec est de source hydrique, ce qui confirme l'omniprésence de l'eau dans l'économie de la province (Hydro-Québec, 2013). Il est donc important d'étudier et d'évaluer les changements subis par les événements extrêmes tels que les inondations, dans un contexte de changement climatique, afin de favoriser une bonne gestion et adopter les stratégies d'adaptation appropriées à l'échelle régionale.

Le changement climatique peut être dû, à la fois, à la variabilité naturelle lié essentiellement à l'activité volcanique, la production solaire et l'orbite de la Terre autour du Soleil, soit à une activité humaine massivement émettrice en gaz à effet de serre. Depuis la révolution industrielle, l'impact de l'activité anthropique sur le climat devient de plus en plus visible, d'ailleurs c'est lui le facteur déterminant sur lequel se base les scénarios climatiques utilisés pour faire des projections future de système climatique. Depuis des décennies, la communauté scientifique ne cesse de développer ses outils et ses modèles pour reconstruire les systèmes atmosphère, terre et océan, et modéliser les liaisons complexes entre eux. Les modèles climatiques globaux avec leurs bilans d'eau et d'énergie fermés, avec ses composants représentants aussi bien l'atmosphère et la terre, sont considérés comme un outil éminent pour comprendre la complexité du système à l'échelle globale. La limitation d'un modèle global vient de sa faible résolution rendant la modélisation de certain processus hydrologique une tache pas trop réaliste. D'où vient le modèle climatique régionale, qu'avec sa fine résolution offre une représentation des processus atmosphériques et de la surface terrestre plus fiable surtout pour l'interaction terre-atmosphère. Nombreuses récentes études ont profité de la technique de la réduction d'échèle dynamique (downscaling), en utilisant les MRC piloté par un modèle global, pour évaluer les impacts des changements climatiques sur les différentes variables du cycle hydrologique (e.g.

Huziy et al., 2012; Clavet-Gaumont et al., 2012; Teutschbein et al., 2012; Tian et al., 2013; Jeong et al., 2014; Bosshard et al., 2014; Charlton et al., 2014).

Le cinquième rapport de GIEC projette, une diminution de 7 % de la surface du manteau neigeux de l'hémisphère Nord au printemps. Pour le Nord Est de l'Amérique incluant le Québec, les scientifiques prévoient une augmentation de la température moyenne annuelle de l'ordre de 2°C et une augmentation de 10 % de la précipitation, avec des différences entre les saisons, pour la période 2081-2100 en se référant à la période 1986-2005 et en utilisant 32 modèles CMIP5 (Coupled Model Intercomparison Project) sous le scenario RCP2.6. Tous ces faits, favorisent le risque d'avoir des crues printanières plus intenses. Donc plusieurs études ont été menées pour évaluer l'impact des changements climatiques sur les caractéristiques des débits de quelques rivières individuellement (e.g. Dibike and Coulibaly, 2007; Quilbé et al., 2008; Minville et al., 2008; Saad et al. 2015). Alors que Huziy et al., (2012) était intéressé à l'étude des changements projetés aux différentes caractéristiques de débit y compris les pointes de crue dans un cadre univariée sur la région nord-est du Canada couvrant 21 bassins du Québec qui est la même région prise en compte dans cette étude. Huziy (2012) a montré que l'impact d'un phénomène d'inondation n'est pas liée seulement à son débit de pointe mais aussi au volume et a la durée de l'évènement. Jeong et al., (2013) a étudié l'impact du changement climatique sur les trois caractéristiques des crues de printemps, à savoir pic de crue, le volume et la durée, pour la même zone d'étude en utilisant l'approche de copula (approche multivariée) et les simulations du Modèle Régional Canadien du Climat (MRCC) et il a approuvé que les trois caractéristiques sont étroitement corrélés deux a deux entre eux.

L'analyse des résultats trouvés à partir d'un MRC doivent être pris avec précaution. Toutefois, l'utilisation d'un MRC amène plusieurs sources d'incertitudes (Bosshard et al., 2014) liées à la formulation du modèle (le choix du domaine, la paraméterisation, les processus physiques...), à la variabilité interne du modèle (déclenchée essentiellement par les conditions initiales) et aussi à la dépendance aux forçage dans les conditions aux limites (choix de MCGA). Toutes ces erreurs doivent être quantifiées pour assurer une bonne lecture des résultats obtenus. D'où vient l'intérêt du cette étude qui s'intéresse a l'évaluation des changements projetées aux caractéristiques des crues printanières au Québec en utilisant plusieurs MRC provenant du projet NARCCAP (North American Regional Climat Change Assessment Program). La zone d'étude couvre 21 bassins versants au Nord Est canadien, principalement situées dans la province du Québec et certaines parties dans l'Ontario et la Terre Neuve et Labrador au Canada. Cette zone a été délimitée par Hydro-Québec/Ouranos, et représente la plupart des principaux basins versants du Québec au nord du fleuve Saint Laurent et a l'ouest du Labrador.

Chaque MRC du projet NARCCAP est caractérisé par une grille spécifique différente aux autres, avec une résolution spatiale horizontale de l'ordre de 50 Km avec des projections différentes. Les simulations des différents MRC adoptent le scénario d'émission de gaz à effet de serre A2 qui est le scénario le plus pessimiste, en haut de peloton des scénarios d'émissions du SRES (Special Report on Emissions Scenarios) publié par GIEC. A2 se caractérise par un accroissement continuel de la population et des émissions des gaz à effet de serre, il semble être le scenario le plus raisonnable et probable vu les efforts modestes pour lutter contre ce phénomène et les enjeux politiques de la tâche. Chaque MRC est piloté par les ré-analyse NCEP et au moins un de quatre MCGA partenaires selon les exigences de NARCCAP. La résolution d'un modèle de circulation générale de l'atmosphère est de l'ordre de 300 km (dans le cas de NARCCAP) ce qui rend la répresentation des bassins versants des rivières inadéquate.

Le recours aux modèles régionaux du climat constitue un choix judicieux et bien justifié, afin de determiner les données de ruissellement utilisées pour deriver les débits d'écoulement ce qui rend l'étude beaucoup plus representative. Tel que indiqué précédemment, l'utilisation de MRC amène plusieurs sources d'erreurs. Donc il faut qualifier et quantifier ses erreurs pour valider les modèles avant d'utiliser ses simulations. Pour se faire, une panoplie des observations est utilisée dans cette étude à savoir : les données des débits quotidiens observés pour 8 stations de jaugeage reparties sur la région de Québec provenant de CEHQ (Centre d'expertise hydrique du Québec; http://www.cehq.gouv.qc.ca/). Ces stations de jaugeages sélectionnés sont dispersées sur la plupart du domaine considéré, représentant diverses conditions hydrologiques allant des petits exutoires montagneux aux grandes surfaces du bassin versant principal.

Une autre variable importante pour les crues printanières est l'équivalent en eau de la neige, cette variable est fournie de Brown et al. (2003) et finalement la température sous forme des données analysées par l'Unité de recherche climatique quadrillée (CRU2; Mitchell et Jones, 2005). L'utilité de ses observations est son utilisation pour quantifier l'erreur de performance des modèles considérés. En effet, les observations de chaque variable ont été comparées avec les simulations correspondantes, issues du MRC considéré, piloté par les ré-analyses NCEP pour la période commune entre les deux. La repartition des stations n'est pas uniforme dans l'espace et n'obèit pas à la régularité d'une grille d'un modèle. Pour remédier è cet obstacle une grille de référence a été choisie avec une résolution horizontale de 45 km qui a servit pour définir les masques des bassins versants au Québec. Cette grille a été utilisée dans plusieurs études (huziy et al., Clavet-Goumont et al., Monette et al., Jeong et al.).

Un autre défit dans la validation d'un modèle climatique régional est la quantification des erreurs dues aux choix de MCGA qui impose les conditions laterales du MRC. En d'autres mots, il faut déterminer la sensibilité d'un MRC au choix de pilotage extérieur. Dans cette étude, la quantification de cette sensibilité est effectuée en comparent les simulations de MRC pilotées par MCGA avec celles pilotées par NCEP.

Dans la plupart des études, l'évaluation des impacts des changements climatiques sur les caractéristiques des crues, a été entamée généralement en adoptant une approche univariée qui donne une information limitée de l'occurrence d'inondation (par exemple Huziy et al, 2012;.. Clavet-Gaumont et al, 2012). Cependant, une inondation est un événement multivariée caractérisé par son pic de pointe, son volume et sa durée (Chebana et Ouarda, 2009; Ben Aissia et al, 2011; Jeong et al, 2014). Par conséquent, il est raisonnable d'étudier les changements appréhendés sur les caractéristiques des crues d'un point de vue multivarié. Certaines techniques ont été développées pour modéliser les caractéristiques des crues multivariées comme une généralisation des distributions univariées (par exemple exponentielle bivariée (Favre et al, 2002); Copula (Jeong et al, 2014)). Copula présente un outil adéquat pour la modélisation des fonctions des distributions conjointes a partir des distributions marginales univariées car elle permet la modélisation de la dépendance entre les variables corrélées (Parent et al., 2014). Nombreuses récentes publications ont utilisé la théorie des copulas pour étudier les distributions multivariées de diverses variables hydrométéorologiques vu la flexibilité de cette technique (Song et al, 2010; Cahill et al, 2011; Chowdhary et al, 2011; Zhang et al., 2011; Kwak et al, 2012; Jeong et al, 2014; Tong et al, 2014).

Il est important de noter que pour les bassins au nord-est du Canada, aucune étude n'a abordé les changements projetés sur les caractéristiques des crues, d'une manière systématique tel que présenté dans cette étude, en utilisant une approche multivariée et en se basant sur des simulations d'ensemble provenant de plusieurs MRC du projet NARCCAP, afin d'évaluer les incertitudes liées à ces modèles.

En bref, dans cette étude, une évaluation des impacts des changements climatiques sur les caractéristiques des crues printanières de mars à juin pour 21 bassins versants de la province de Québec en utilisant plusieurs modèles climatiques régionaux du projet NARCCAP, est effectuée pour une période de référence de 1971-2000 et une période de climat future visée de 2041-2070. Cette étude est basée sur une approche multivariée utilisant Copula. Les simulations utilisées proviennent du projet NARCCAP et correspondent aux MRC suivants : CRCM (OURANOS / UQAM), le HRM3 (Hadley Centre) et le WRFG (Pacific Northwest National Lab / NCAR). Aux moments de la réalisation de cette étude, seules ces trois simulations fournissent le ruissellent, qui est utilisé pour le calcul des débits à l'aide du schéma de routage WATROUTE. Les MRCs considérés sont pilotés par les ré-analyses NCEP ainsi que quatre MCGA : le CCSM (NCAR), le CGCM3 (CCCMA), le GFDL (NOAA) et HadCM3 (Hadley centre) pour la simulation du climat présent et futur. Un total de six combinaisons des MRC-MCGA sont utilisées pour les projections climatiques et trois simulations RCM-NCEP sont comparées avec les observations. Toutes les simulations et les observations sont interpolées sur la meme grille dont la résolution est de 45x45 km.

Les principaux objectifs de cette étude sont :

- Évaluer et quantifier les erreurs de performance des MRCs en comparent les variables simulées des crues (débits, EEN et la température), avec celles observées.

- Effectuer l'analyse statistique des moyennes des caractéristiques des crues printanières (i.e. pic, volume et durée) et leurs niveaux de retour pour 5 et 30 ans.
- Analyser et quantifier les erreurs associées au choix de forçage aux frontières (pilotage) c'est-à-dire comparer chaque MRC-MCGA par rapport à la simulation de référence MRC-NCEP correspondante pour les caractéristiques moyennes des crues, pour leurs niveaux de retour de 5- et 30-ans et pour leurs probabilités conjointes de présence en utilisant Copula.
- Estimer les changements appréhendés pour les caractéristiques moyennes des crues, pour leurs niveaux de retour et pour leurs probabilités conjointes de présence pour la période 2041-2070.
- Analyser et discuter les résultats obtenus.

Organisation du mémoire :

À la suite de l'introduction présentée ci-haut, un article rédigé en anglais fera office de chapitre II pour ce mémoire et remplacera donc les chapitres II (méthodologie) et III (résultat) présents normalement dans un mémoire. Cet article comprend les sections suivantes: (1) l'introduction comprenant la revue littéraire et le contexte de l'étude, (2) la description des modèles et du domaine, (3) la méthodologie, (4) la présentation des résultats et (5) discussion et conclusion. Finalement, le chapitre III présentera les résultats de cette étude sous forme de discussion.

CHAPITRE II

PROJECTED CHANGES TO FLOOD CHARACTERISTICS FOR NORTHEAST CANADA BASED ON THE NARCCAP MULTI-RCM ENSEMBLE AND MULTIVARIATE FREQUENCY ANALYSIS APPROACH

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2.1. INTRODUCTION

The fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013) reported that observed global mean surface temperature has increased by 0.85°C for the 1880-2012 period. AR5 reported a likely increase in precipitation, in terms of frequency and intensity for the northern hemisphere (NH) mid-latitude land areas (Kharin et al., 2013). In addition, the report also documented an increase of global near surface and troposphere air specific humidity since the 1970s and decrease of snow cover extent by about 0.8×10^6 Km^2 per decade for the same period in the northern hemisphere (Brown and Robinson, 2011), especially in spring (Stocker et al., 2013). For North America, a future increase in the intensity and frequency of precipitation is projected by Christensen et al. (2007) which is confirmed by Collins et al. (2013), accompanied by an increase of temperature, particularly over high-latitude regions. These increases can have an impact on the snow season length and on the snow depth that are expected to decrease over most of North America. All this could lead to an earlier and larger spring runoff, as noted in Hanna et al. (2008), Cao et al. (2010), and Gosling et al. (2011), based on global and basin-scale hydrological models. These changes in spring runoff can significantly affect flood dynamics in the Canadian river basins where high flows are essentially generated due to spring snowmelt (Mareuil et al., 2007). Such changes impact society and can cause enormous environmental, social, and political repercussions. For instance, Hydro-Québec reported that 96% of the total energy produced in the province of Quebec is hydro-based and therefore stability of water resources is very important to the economy of the province (Hydro-Québec, 2013). It is therefore important to investigate projected changes to the characteristics of extreme events such as floods in the context of a changing climate to support proper management and adaptation strategies at regional scale.

Atmosphere Ocean Global Climate Models (AOGCMs), with their complete closed water budget including both the atmospheric and land surface branches, are the comprehensive tools used to generate information about present and future climates following various scenarios proposed by IPCC. For instance, AOGCM simulations can be used to understand better the linkages and feedbacks between climate and hydrological systems, and to evaluate the impact of climate change on various hydro-meteorological variables. However, AOGCMs, because of their coarse resolution, have difficulties to simulate extreme weather events with the intensity and frequency comparable to what is observed, particularly precipitation extremes (Wehner, 2010 and Orlowsky et al., 2011). Regional Climate Models (RCMs) can overcome this limitation by offering higher spatial resolution compared to AOGCMs, allowing greater topographic realism and finer-scale atmospheric dynamics to be simulated and thereby better represent extremes at local and regional scales. Many recent studies have used RCMs to evaluate projected changes to various components of the hydrological cycle including mean, seasonal and extreme flows in their studied regions (e.g. Huziy et al., 2012; Clavet-Gaumont et al., 2012; Teutschbein et al., 2012; Charlton et al., 2012; Tian et al., 2013; Jeong et al., 2014; Bosshard et al., 2014).

RCMs are associated with various sources of uncertainties (Bosshard et al., 2014), including (1) structural uncertainty associated with model formulation (e.g., domain size and location, physical processes and parameterization), (2) internal variability (triggered by differences in the initial conditions), and (3) dependence on lateral boundary forcing (i.e., choice of the AOGCM). To evaluate these uncertainties, the use of multi-RCM ensemble becomes indispensable. The North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2013; Khaliq et al., 2014) is such a multi-RCM ensemble project over North America.

Assessment of climate change impacts on flood characteristics has been generally studied based on a univariate approach, which provides only limited information about the probability of flood occurrences (e.g. Huziy et al., 2012; Clavet-Gaumont et al., 2012). However, a flood is a multivariate event characterized by its peak, volume and duration (Chebana and Ouarda, 2009; Ben Aissia et al., 2011; Jeong et al., 2014). Therefore, it is reasonable to study ` changes to flood characteristics from a multivariate viewpoint. Some techniques have been developed to model multivariate flood events as a generalization of the univariate approach, e.g. bivariate exponential distribution (Favre et al., 2002); copula based bi- and trivariate analyses (e.g. Karmakar and Simonovic, 2008; Jeong et al., 2014). Many recent studies have used copula approaches to investigate multivariate distributions of various hydro-meteorological variables, due to their flexibility (Song et al., 2010; Cahill et al., 2011; Chowdhary et al., 2011; Zhang et al., 2012; Kwak et al., 2012; Jeong et al., 2014; Tong et al., 2014; Jiang et al., 2015). Therefore, Copula based multivariate framework is a reasonable approach for modelling joint distribution functions from univariate marginal distributions as it allows modelling the dependence between two or more correlated variables (Parent et al., 2014)

This study is focused on the province of Quebec which plays a significant role in the Canadian economy due to its large number of hydroelectric power generating stations. According to the AR5 (IPCC, 2014), eastern North America including middle and southern parts of Québec is projected to experience an increase in the annual mean temperature of the order of 2°C and precipitation by 10% under the RCP2.6 scenario based on 32 CMIP5 (Coupled Model Intercomparison Project Phase 5) simulations for the 2081–2100 period with respect to the 1986–2005 period. For this region, some previous studies have been performed to investigate changes to streamflow characteristics for few individual river basins (e.g. Dibike and Coulibaly, 2007; Quilbé et al., 2008; Minville et al., 2008; Saad et al. 2015). However, Huziy et al. (2012) studied projected changes to various streamflow characteristics including flood peaks in a univariate setting over the entire northeast Canadian region, covering all Quebec basins, which is also the region considered in this study. Also, Jeong et al., (2013) studied the impact of climate change on three spring flood characteristics (i.e., flood peak, volume and duration) for the same study area using the multivariate copula approach and the Canadian Regional Climate Model simulations. It is important to note that for the northeast Canadian basins, no study has addressed so far projected changes to flood characteristics within a multivariate setting using a multi-RCM ensemble.

In this study, projected changes to three spring flood characteristics (i.e., flood peak, volume and duration) within a multivariate framework, for 21 northeastern Canadian basins using multi-RCM ensemble, which permits evaluation of various uncertainties, are assessed. A set of six simulations from three RCMs for current (1971-2000) and future (2041-2070) climates, driven by four different AOGCMs, are considered. To assess projected changes NCEP (National Center for Environmental Prediction) driven RCM simulations are compared to observations for assessing performance errors. Conventional univariate frequency analysis is performed for individual flood characteristics and copula based bivariate frequency analyses for three pairs of flood characteristics (i.e., peak-volume, peak-duration and volume-duration).

This paper is organized as follows. In section 2, RCM simulations as well as observed streamflow, temperature and snow water equivalent (SWE) data are presented. Section 3 is devoted to the methodology adapted for assessing the performance of RCMs, as well as evaluation of projected changes to flood characteristics. Detailed results of the study are presented and discussed in Section 4 and main conclusions are provided in Section 5.

2.2. SIMULATIONS, OBSERVATIONS AND STUDY AREA

2.2.1 NARCCAP RCM simulations

Flood characteristics are derived from the multi-RCM simulations available through NARCCAP. All RCMs have been driven by NCEP reanalysis II and two distinct AOGCMs over the North American domain covering Canada, USA and most of Mexico for the IPCC's Special Report on Emissions Scenarios (SRES) A2 scenario. It is important to note that all RCMs use different projections but the same horizontal resolution of 50 km. Detailed description of model characteristics is available from NARCCAP (www.narccap.ucar.edu/data/rcm-characteristics.html), Mearns et al. (2009), and also from the individual modelling group's website.

This study employs simulations from three RCMs (i.e. CRCM, HRM3 and WRFG), which provide runoff needed to generate streamflow, driven by NCEP reanalysis II and four AOGCMs (i.e. CCSM, CGCM3, HadCM3 and GFDL). Table 1 shows acronyms and full names of various RCM-AOGCM pairs: CRCM and WRFG are driven by CCSM and CGCM3, and HRM3 is driven by HadCM3 and GFDL. The NCEP-driven simulations are available for the 1980–2004 period, while the AOGCM-driven simulations are available for the current 1971–2000 and future 2041–2070 periods. The NCEP-driven simulations are used to assess performance errors associated with streamflow hydrographs and spring flood related variables, while AOGCM-driven current and future period simulations are used in the assessment of projected changes to flood characteristics. Throughout this article, different RCM simulations will be referred to as 'RCM-LBC', where RCM refers to the acronym of the RCM and LBC to the respective lateral boundary condition, i.e., NCEP or the AOGCM driving the regional model at the boundaries.

2.2.2 Streamflow simulations

This study focuses on the Northeastern part of Canada, which consists of 21 watersheds located mainly in the Quebec province of Canada (Figure 1). Runoff values simulated by RCMs are used to generate streamflow based on a modified version of the WATROUTE routing scheme, following Poitras et al. (2011). The routing scheme is based on a cell-to-cell routing framework. Flow directions, river lengths and their slopes employed in the routing scheme are estimated based on HydroSHEDS data (Lehner et al., 2008; Huziy et al., 2012). Poitras et al. (2011) provide detailed description on streamflow calculation from RCM-simulated runoff.

2.2.3 Observed data

Observed daily streamflow data from 8 gauging stations for the Québec region (Figure 1) are obtained from CEHQ (Centre d'expertise hydrique du Québec; http://www.cehq.gouv.qc.ca/) dataset. Information about the gauging stations (i.e., location, representative drainage area, and annual mean flow) is provided in Table 2. These selected stations are scattered over most of the study domain, representing various hydrological conditions ranging from small mountainous basin outlets to large basin main stream outlets, with drainage areas ranging from 2.28 to 33.9 km^2 and annual mean flow from 49.1 to 504.5 m^3/s.

Observed dataset of SWE is obtained from Brown et al. (2003). This dataset was produced by applying the snow depth analysis scheme developed by Brasnett (1999) to generate a 0.3° latitude/longitude grid of daily and monthly mean snow depth and corresponding estimated water equivalent for North America. This observational dataset was produced for the 1979–1997 period. The gridded Climatic Research Unit

(CRU2; Mitchell and Jones, 2005) dataset is used to validate simulated temperature in this study .

2.3. METHODOLOGY

2.3.1 Reference grid

In order to ensure a better comparison between different RCM simulations, a reference grid is highly desirable. The selected reference grid has a horizontal resolution of 45 km and polar-stereographic projection. This grid has been used in a number of previous studies across Canada. Before performing any analysis, all model-simulated data were interpolated to this reference grid using the inverse distance squared method (http://www.ncl.ucar.edu/), while the observed data were aggregated to the same reference grid.

2.3.2 Flood risk analysis

2.3.2.1 Identification of flood characteristics

A flood event can be characterised by its peak, volume and duration as illustrated in Figure 2. A fixed threshold approach is used in this study to determine flood characteristics. This approach assumes a threshold discharge and considers upper part of the hydrograph as a flood event (Grimaldi and Serinaldi 2006; Karmakar and Simonovic 2008; Jeong et al., 2014). Besides the flood peak, a flood event is also characterized by its duration which is identified by determining time points corresponding to rise in discharge from the threshold (start date) and return to threshold (end date) as shown in Figure 2 (Karmakar and Simonovic, 2008). The associated flood volume is determined by removing the base flow from the total volume of streamflow over the flood duration. For the present work, following Jeong et al. (2014), the fixed threshold is taken as 1.3μ, where μ is the mean annual streamflow. There is a greater possibility for the base flow to be included in the identified flood event if too small a threshold is selected. On the other hand, a very large threshold will result in the exclusion of large amounts of flood flow volume. Jeong et al. (2014) selected 1.3μ threshold as it provides a reasonable compromise to address the above mentioned contrasting extreme conditions. In addition, this threshold is also found suitable for all observation stations and CRCM grid points in the study area.

2.3.2.2 Marginal and joint distributions

Marginal frequency analysis is developed on the basis of seasonal maximum values of flood characteristics. Following results of Jeong et al. (2014), the Generalized Extreme Value (GEV) distribution is used to model marginal distributions of the three flood characteristics. From these marginal distributions, a bivariate distribution function is developed following the copula approach.

The copula theory has been used to construct joint distributions of multiple variables by connecting multivariate probability distribution to its one-dimensional marginal probability distribution functions (Nelsen 1999). Let X and Y be two random variables with the marginal cumulative distribution functions (CDFs) F_X and F_Y, the joint cumulative distribution function of (X, Y), $F_{XY}(x, y)$, can be expressed as:

$$F_{XY}(x,y) = C[F_X(x), F_Y(y)] \qquad (1)$$

where C is a bivariate copula of (X, Y). If $F_X(x) = u$ and $F_Y(y) = v$, the expression (1) can be written as follows:

$$C(u,v) = F_{XY}[F_X^{-1}(u), F_Y^{-1}(v)], \quad (u,v) \in [0,1]^2 \qquad (2)$$

where F_X^{-1} and F_Y^{-1} are generalized inverses of F_X and F_Y, respectively.

Nelsen (1999) suggested a number of copula families (e.g., Archimedean, elliptical and extreme value) to construct multivariate probability distribution functions. For hydrological studies, the Archimedean copula family offers many advantages (Zhang and Singh 2006): the Archimedean family is easy to construct and numerous copula models belong to this class (McNeil and Neslehovà 2009). Furthermore, this family is also applicable for both positively and negatively correlated variables. Some Canadian studies have used this family for single-site bivariate flood frequency analysis (e.g. Favre et al. 2004; Aissia et al. 2011; Karmakar and Simonovic 2009). A bivariate Archimedean copula can generally be expressed as:

$$C_\theta(u,v) = \emptyset^{-1}[\emptyset(u) + \emptyset(v)] \qquad (3)$$

where subscript θ of copula C is parameter hidden in the generating function ϕ. For the Archimedean copula, θ can be determined from the relationship between KCC (Kendall's correlation coefficient) τ and generating function $\phi(t)$, which is defined by $\tau = 1 + 4\int_0^1 \frac{\emptyset(t)}{\emptyset'(t)} dt$ (Karmakar and Simonovic, 2009), where $t = u$ or v. The KCC τ is a well-known nonparametric measure of dependence between any two (X and Y) random variables. In this study, the Archimedean Clayton copula is used following Jeong et al. (2014). The equation, generating function $\phi(t)$ and relationship between θ and τ for this copula are respectively given by:

$$C_\theta(u,v) = [u^{-\theta} + v^{-\theta} - 1\,]^{\frac{-1}{\theta}} \quad \theta \in (0,\infty) \qquad (4)$$

$$\emptyset(t) = t^{-\theta} - 1 \qquad (5)$$

$$\tau = \frac{\theta}{\theta + 2} \qquad (6)$$

In this study, a joint occurrence probability is investigated which is defined as the probability of both X and Y exceeding simultaneously their respective thresholds, i.e. $P(X > x \text{ and } Y > y)$. Here x and y denote the values of X and Y corresponding to a selected return period. Following Yue and Rasmussen (2002) and Liu et al. (2011), this probability is formulated as:

$$\begin{aligned} P(X > x \text{ and } Y > y) &= 1 - F_X(x) - F_Y(y) + F_{XY}(x,y) \\ &= 1 - F_X(x) - F_Y(y) + C[F_X(x), F_Y(y)] \qquad (7) \end{aligned}$$

For both x and y, flood peak, volume and duration corresponding to 5- and 30-year return periods for the current climate are used. The joint occurrence probabilities of peak–volume, peak–duration and volume–duration pairs for the current climate and their projected changes for the future climate are studied. The joint occurrence probability $P(X > x \text{ and } Y > y)$ for an r-year return period is denoted by P_r.

2.3.2.3 Performance and lateral boundary forcing Errors

Simulated temperature and SWE from the RCM-NCEP simulations and streamflows generated from the WATROUTE model are compared to those observed, to assess performance errors, i.e., errors due to the internal dynamics and physics of each RCM. The lateral boundary forcing errors are also assessed by comparing flood characteristics derived from RCM-AOGCM simulations, for the current 1980–2000 period, to those derived from RCM-NCEP simulations for the same time period.

2.4. RESULTS

2.4.1 Basics statistics

2.4.1.1 Assessment of errors

a) Performance errors

Biases in winter (DJF) SWE are estimated by comparing mean winter SWE from CRCM, HRM3 and WRFG simulations driven by NCEP reanalysis with those from the gridded North American SWE data from Brown et al. (2003) for the 1980–1997 period (Figure 3a). For CRCM-NCEP, positive performance errors are noted for most part of the domain, with the magnitude of errors increasing from south to north. The spatial pattern of the performance errors for HRM3-NCEP appears to divide the study area into two parts: positive for northern half and negative for the southern half of the domain. WRFG-NCEP underestimates observed SWE for most of the considered watersheds, except those located in the very north. HRM3 and WRFG underestimate winter SWE for the southern part of the domain. This fact could imply reduced winter runoff and streamflow over this region. Spring (MAM) temperature biases presented in Figure 3b are estimated by comparing mean temperature from CRCM, HRM3 and WRFG simulations driven by NCEP with those from the gridded Climatic Research Unit (CRU2; Mitchell and Jones 2005) data for the 1980-1999 period. These results suggest an overestimation of temperature by all three simulations for the central and northern regions, with the biases being larger for CRCM and HRM3. An underestimation of spring temperature is noted for southern basins by all RCM simulations.

Observed and modelled hydrographs (mean daily streamflows) are compared at the selected stations in Figure 4. The modelled hydrographs are derived from CRCM-NCEP, HRM3-NCEP and WRFG-NCEP simulations. There are large differences between observed and modelled hydrographs both in the magnitude and timing of peak flows, which can partly be explained by the biases in the winter SWE and spring temperature of the RCMs. For instance, CRCM-NCEP generally yields larger and early peaks compared to the observations for the northern stations 104001, 93801, 93806 and 103715. These results can be explained by the overestimation of winter SWE for the upstream regions and positive biases in the spring temperatures for these stations. However, CRCM-NCEP underestimates flood peak magnitudes for the central gauging stations (i.e., 81006, 92715, and 61502). Streamflows generated from HRM3-NCEP and WRFG-NCEP simulations underestimate observed flood peak magnitudes for the southern gauging stations 40830, 61502 and 81006 during the spring period. This negative bias can be attributed to the underestimation of winter SWE by this models for southern basins mentioned before, which affect spring flood peak. In general, for all basins and for the three RCMs, simulated peaks occur earlier than observed. This behaviour is believed to be due to the positive temperature biases (Figure 3b) during spring (MAM).

b) Boundary forcing errors

Boundary forcing errors are assessed by comparing mean spring flood characteristics derived from AOGCM-driven simulations with those from NCEP-driven simulations for the 1980-2000 period. Results shown in Figure 5a suggest that the spatial patterns of mean peak flows are about similar for RCM-NCEPs and RCM-AOGCMs. Positive boundary forcing errors are noted for mean peak flows simulated by CRCM-CGCM3 and CRCM-CCSM for the entire Quebec region, except for small negative errors shown by CRCM-CCSM for one south-western watershed. For HRM3, mean peak flood from AOGCM-driven simulations are larger than those from NCEP-driven simulations for the central regions. A clear disagreement between HRM3 simulations driven by two AOGCMs for southern watersheds can be noticed; HRM3-GFDL shows negative errors while HRM3-HadCM3 shows small positive errors. Most watersheds located in the north and central parts show positive boundary forcing errors for WRFG-CCSM and WRFG-CGCM3. Overall, larger errors are associated with CRCM-CCSM and HRM3-HadCM3 and smaller errors with HRM3-GFDL. It should be noted that the influence of the driving AOGCM on the mean peak flow is considerable. In fact, for each RCM, simulations driven by two different AOGCMs exhibit very different behaviours for a number of watersheds.

Based on the results shown in Figure 5b, mean flood volumes generated by RCM-NCEPs are about similar to those generated by RCM-AOGCMs. Larger boundary forcing errors are associated with CRCM-CCSM and WRFG-CGCM3, compared to other RCM-AOGCM combinations, where positive errors are noted for most of the watersheds. Mean flood volumes for all RCM-AOGCM simulations are larger than those for NCEP-driven simulations for the northern basins, except for HRM3-HadCM3. Negative boundary forcing errors are noted for the southern basins for HRM3-GFDL. It is notable that spatial paterns of the boundary forcing errors of RCM-AOGCM simulations for the flood volume are simlar to those for the flood peak presented in Figure 5a. The comparison between mean flood duration values simulated by RCM-AOGCM and those simulated by RCM-NCEP suggest, as shown in Figure 5c, positive boundary forcing errors (larger than 20%) for CRCM-AOGCMs and WRFG-AOGCMs for almost the entire study domain. HRM3-AOGCMs show positive errors for the central basins and negative errors for the northern and southern watersheds.

c) Projected changes

Projected changes to the mean values of flood characteristics are obtained by comparing flood characteristics simulated by RCM-AOGCMs for future period to those for the current period. In Figure 5, mean values of flood characteristics for the RCM–AOGCMs for the current climate are shown in the second column and their projected changes are shown in the fourth column. For the flood peak (Figure 5a), an increase in future mean peak flow is suggested by CRCM-CCSM, HRM3-AOGCMs and WRFG-CCSM for the central and southern basins. CRCM-CGCM3 and WRFG-CGCM3 generally suggest an increase in future peak flow, except for some southern basins. For the flood volume (Figure 5b), an increase in the mean flood volume is expected in the future climate, mainly for the western basins based on CRCM-AOGCMs, HRM3-HadCM3 and WRFG-CCSM. However, rest of the model simulations project an increase in the future for the eastern regions. It is noted that the largest increase is simulated by CRCM-CCSM. A future increase in the mean flood duration is simulated by most of the models for the entire domain, particularly for the central and southern basins with large values associated with WRFG-CCSM (Figure 5c).

2.4.2 Univariate analysis

2.4.2.1 Boundary forcing errors

Lateral boundary forcing errors for 5- and 30-year return levels of the three flood characteristics are shown in Figures 6 and 7. Results of 5-year return levels of flood peak (Figure 6a) suggest that return values of AOGCM-driven simulations are considerably larger than those of NCEP-driven simulations for most of the watersheds and for most RCM-AOGCMs, except for CRCM-CCSM, which shows negative boundary forcing errors for southern and east-central basins. The lateral boundary forcing errors are relatively larger for HRM3 and WRFG compared to CRCM. For the 30-year return levels of flood peaks (Figure 7a), the differences between NCEP-driven and AOGCM-driven RCM simulations are similar to those of 5-year return levels in terms of spatial pattern of errors, with larger values associated with the 30-year return levels. The influence of the driving AOGCM is obvious for CRCM and WRFG as they show large differences for this statistic based on their driving AOGCMs. Larger boundary forcing errors are associated with WRFG-AOGCMs and CRCM-CGCM3 compared to the other models.

The behaviour of boundary forcing errors associated with the 5-year return levels of flood volume (Figure 6b) is comparable to that of flood peak with larger values for the latter characteristic. RCM-AOGCMs produce larger values than RCM-NCEPs for most of the regions, except for CRCM-CCSM, which suggests small negative differences for the southern and east-central basins. Larger boundary forcing errors are associated with CRCM-CCSM and HRM3-GFDL compared to the other RCM-AOGCM combinations. Similar differences for the 30-year return levels of flood volume are found for NCEP-driven and AOGCM-driven simulations (Figure 7b). Small boundary forcing errors are associated with HRM3-AOGCM simulations, whereas large errors are associated with WRFG-CCSM.

For the flood duration associated with 5-year return levels (Figure 6c), positive boundary forcing errors are noted for most of the model combinations and for most of the basins with larger errors associated with HRM3-AOGCMs compared to the other model combinations. The comparison between 30-year return levels of flood duration simulated by RCM-AOGCMs and those simulated by RCM-NCEPs (Figure 7c) suggest large positive boundary forcing errors (larger than 30%) for most of the RCM-AOGCM combinations analysed. It should be noted that the influence of the driving AOGCMs on various return levels for the three flood characteristics is considerable as the lateral boundary forcing errors could differ in magnitude across various basins for all RCM-AOGCM combinations. It is also important to note that larger values of boundary forcing errors in 5- and 30-year return levels are associated with flood duration compared to flood peak and volume. Boundary forcing errors associated with the 30-year return levels of three flood characteristics are larger than those associated with the 5-year return levels.

2.4.2.2 Projected changes

Future projected changes to 5- and 30-year return levels of flood characteristics are shown in the fourth column of Figures 6 and 7. For the 5-year return levels of flood peak, the CRCM-AOGCMs project a small increase (less than 20%) for the central and southern basins. HRM3-AOGCMs and WRFG-CCSM suggest a decrease in future return levels of flood peak for several southern basins. The results shown in the fourth column of Figure 6b suggest future increases in the 5-year return levels of flood volume based on some RCM-AOGCMs for the majority of the grid points in the study area. HRM3-AOGCMs and WRFG-CCSM project a future decrease for several southern basins, which is consistent with the projected changes in the 5-year return levels of flood peak. It should be noted that the percentage of projected changes in the 5-year return levels of flood volume are larger than those of flood peak for the same return period and this can be due to the future increase in the 5-year return levels of flood duration. Results of projected changes in the 5-year return levels of flood duration (Figure 6c) show an increase in future for most of the basins and models. Larger increase (large than 40%) is projected by all models for the central and northern regions.

The spatial pattern of future changes to the 30-year return levels of flood peak (Figure 7a) is similar to that of the 5-year return levels with larger errors for the 30-year return period. The pair of WRFG-AOGCM simulations projects a future increase for the west central basins but no significant changes for the rest of the domain except some southern basins, where a decrease is projected by WRFG-CCSM. CRCM-AOGCMs and HRM3-AOGCMs suggest positive changes for most of the basins. It is noted that largest changes are associated with CRCM-CGCM3. For the 30-year return levels of flood volume, a future projection which is consistent with that of the 5-year return level is shown in Figure 7b. CRCM-AOGCMs, HRM3-HadCM3 and WRFG-CGCM3 project a larger increase (larger than 20%) for most of the grid points of the study area, while HRM3-GFDL and WRFG-CCSM suggest a future decrease for some southern watersheds and an increase for the central and northern basins. For the flood duration, a future increase in the 30-year return levels for most of the watersheds is simulated by most of the RCM-AOGCM simulations. It is important to note that the estimation of marginal 30-year return values is more uncertain than the 5-year return levels.

2.4.3 Bivariate analysis

2.4.3.1 Boundary forcing errors

The boundary forcing errors associated with the joint occurrence probability for the flood peak-volume pair corresponding to 5-year return level (third column in Figure 8a) generally show positive errors for the six simulations for most of the study region, except WRFG-AOGCMs which show some negative errors for several southern basins. Large boundary forcing errors are associated with WRFG-AOGCMs, whereas small errors are associated with CRCM-CCSM. The joint occurrence probability of the peak-volume pair for the 30-year return level (third column in Figure 9a) simulated by CRCM-AOGCMs shows positive boundary forcing errors for the central and southern watersheds while CRCM-CCSM shows negative errors for northern watersheds. The pair of HRM3-AOGCMs shows positive boundary forcing errors for the joint occurrence probability corresponding to 30-year return period thresholds of peak-volume pair for most grid points of the study domain. WRFG-CCSM and WRFG-CGCM3 show positive errors for the entire domain with some southern basins associated with negative errors. Larger boundary forcing errors are associated with WRFG-AOGCMs compared to the other simulations.

For the peak-duration pair of flood characteristics (Figure 8b), results of joint occurrence probability corresponding to 5-year return period threshold show large values for RCM-AOGCMs compared to those for RCM-NCEPs for a large number of watersheds. CRCM-CCSM and CRCM-CGCM3 show positive boundary forcing errors for the entire study domain. The HRM3-AOGCM and WRFG-AOGCM simulations pairs produce larger joint occurrence probability (more than 20%) than their NCEP driven simulations for the 5-year return level. Joint occurrence probability of CRCM-AOGCMs for the peak-duration pair of 30-year return level shows positive boundary forcing errors for most of the watersheds. HRM3-AOGCM and WRFG-AOGCM show positive differences for most of the grid points of the domain with some negative errors dispersed across some basins, especially for northern basins based on simulations of WRFG-AOGCMs pair and central basins based on HRM3-GFDL simulation. Smaller boundary forcing errors are associated with CRCM-AOGCM.

For the flood volume-duration pair corresponding to 5-year return level (third column in Figure 8c), WRFG-CGCM3 suggests positive boundary forcing errors for most of the studied basins. CRCM-AOGCMs show negative bias for the eastern and southern basins, while HRM3-AOGCMs do not show any specific spatial pattern as positive and negative errors are noted over the study area. CRCM-CCSM shows positive boundary forcing errors for the joint occurrence probability corresponding to 30-year return levels of volume-duration pair (third column in Figure 9c), for most of the watersheds except the central eastern basins where it shows negative bias. CRCM-CGCM3 shows positive errors for the central and southern basins and negative errors for the remaining basins, while HRM3-AOGCMs and WRFG-AOGCMs provide positive errors for most of the basins.

2.4.3.2 Projected changes

Projected changes to joint occurrence probability of flood characteristics are assessed by comparing RCM-AOGCM simulated values for the current 1971-2000 and future 2041-2070 periods. These changes are shown in the fourth column of Figures 8 and 9 for 5- and 30-year return levels, respectively. For both current and future periods, joint occurrence probability P is calculated using thresholds estimated from the marginal distributions for the current climate as presented in the methodology section.

For the peak-volume pair, corresponding to 5-year return level (fourth column in Figure 8a), larger increases in P for the central and southern basins, smaller decreases for the north-eastern basins are suggested by CRCM-CCSM and CRCM-CGCM3 simulations. HRM3-AOGCMs and WRFG-CCSM suggest future increases (less than 20%) for the majority of the basins, while WRFG-CGCM3 suggests future values of P relatively similar to those in the current period for the west-central regions and future increases for the rest of the domain. For the joint occurrence probability corresponding to 30-year return level (fourth column in Figure 9a), the pattern of the projected changes is similar to that for the 5-year return level. CRCM-AOGCMs and HRM3-AOGCMs suggest an increase in the joint occurrence probability of peak-volume pair associated with the 30-year return level for most of the basins, while WRFG-AOGCMs produce increases for the entire region, except the west central basins where simulations project near normal values of P.

Results of projected changes to the joint occurrence probability corresponding to 5-year return level of peak-duration pair are consistent with the corresponding results projected for the 5-year return level of peak-volume pair. CRCM-AOGCMs suggest a future increase in the statistic for the central and southern basins while a future decrease for few north eastern basins is suggested by CRCM-CCSM. The HRM3-AOGCMs and WRFG-AOGCMs project a smaller increase in the probability that peak and duration of floods exceed simultaneously their fixed thresholds for most of the basins, except the west central region where the HRM3-AOGCMs project values closer to those for the current period. CRCM-AOGCMs and HRM3-AOGCMs project an increase in the joint occurrence probability corresponding to the 30-year return level of peak-duration pair for the entire domain, except the central basins, while WRFG-AOGMs suggest an increase in the probability in the future for the entire domain of study. Overall, larger increases are associated with CRCM-AOGCMs.

Based on all RCM-AOGCMs, an increase in the future P values (larger than 20%) corresponding to 5-year return period thresholds is projected for most of the basins. Same changes are expected for the joint occurrence probability associated with 30-year return period, except the central basins where CRCM-AOGCMs and HRM3-AOGCMs project future P values closer to those of the current simulations. Here also, the influence of the choice of driving AOGCM on the percentage of projected changes in P values is noted over many basins.

2.5. CONCLUSIONS

In the present study, climate change impacts on three spring (March to June) flood characteristics (i.e., peak, volume and duration) for 21 watersheds located mainly in the Quebec province of Canada are assessed. Univariate and copula based bivariate frequency analyses are used to develop projected changes based on simulations produced with three different RCMs available from NARCCAP for current (1970-1999) and future (2041-2070) climates. In order to evaluate the performance of RCMs, simulated hydrographs of RCM-NCEPs are compared with those observed at eight selected gauging stations. Moreover, results of univariate and bivariate frequency analyses of RCM-AOGCMs are compared to those from RCM-NCEPs in order to evaluate boundary forcing errors.

From the various analyses presented and discussed in this paper, the following conclusions can be drawn:

- Comparison of hydrographs of NCEP-driven RCM simulations against those at selected gauging stations suggests that the behaviour of RCM simulated hydrographs, peak flows and time to peak depends on the geographic locations of selected stations. For the northern and some southern stations, CRCM overestimates flood peaks, mostly related to the overestimation of winter precipitation that led to the overestimation of winter SWE for the upstream regions. The timing of peaks was earlier than observed and is due to the overestimation of spring temperature at these stations. HRM3 shows negative performance errors for the southern gauging stations, and is due to the underestimation of SWE over this region. However, it performs relatively well for northern watersheds. WRFG performs well on the estimation of flood peaks for most of the southerly stations.

- Spatial patterns of lateral boundary forcing error differ with flood characteristics and RCM-AOGCM combinations. In general, CRCM-AOGCMs and HRM3-AOGCMs provide smaller errors compared to WRFG-AOGCMs for the three flood characteristics. RCM-AOGCMs particularly show smaller errors for the southern basins for basic statistics and univariate analyses.
- Based on the comparison of current and future period RCM-AOGCM simulations, an increase in the mean values of all three flood characteristics is noted. It is important to mention that some differences exist between basins and between different combinations of RCMs and AOGCMs.
- Results show an increase in the projected changes of selected marginal return levels of flood peak, volume and duration for the majority of the basins studied. These findings are consistent with previous findings of Huziy et al. (2012) and Clavet-Gaumont et al. (2012) for flood peaks and those of Jeong et al. (2014) for the three flood characteristics for the same 21 watersheds.
- Projected changes to the joint occurrence probability P of the three pairs of flood

characteristics (i.e., peak-volume, peak-duration and volume-duration) are studied for the very first time based on a multi-RCM ensemble for the 21 watersheds considered in this study. Results show important regional differences and differences related to the choice of the RCM and driving fields. Projections suggest future increases in P, with lager increases for longer return period thresholds (i.e. 30-year) than shorter return period thresholds (i.e. 5-year).

The results of this study will be useful to support proper management and adaptation strategies in many sectors, particularly energy sector. Though the model uncertainty is considered by using six RCM-AOGCM combinations, the assessment is limited to only Quebec province and the SRES A2 emission scenario. A more comprehensive evaluation of flood risk would involve a much broader set of RCMs and AOGCMs than considered in this study. An expanded set of emission scenarios is also necessary to properly evaluate scenario-related uncertainties in the future projections of flood characteristics.

FIGURES

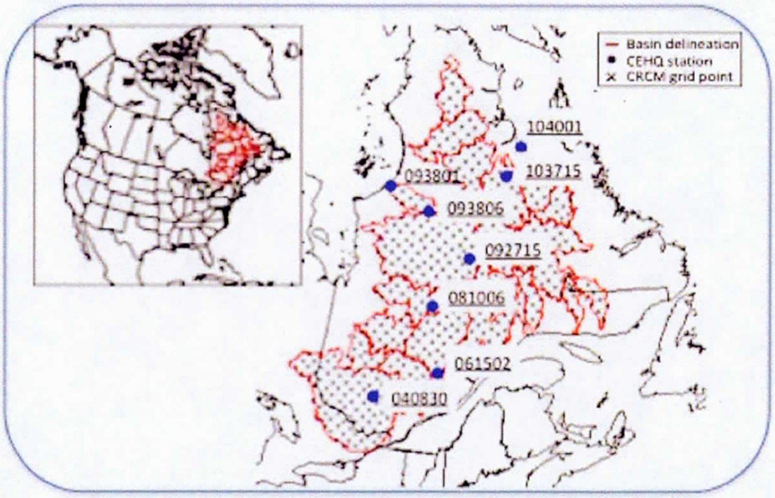


Figure 1. Study area with the selected CEHQ (Centre d'expertise hydrique du Québec) stream gauging stations (Huziy et al.,2012, Jeong et al., 2014).

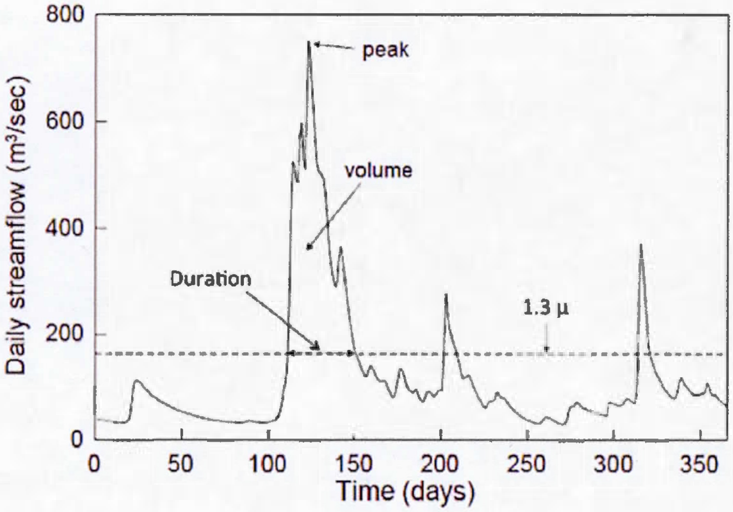


Figure 2. A schematic diagram showing flood characteristics (peak, volume and duration) based on fixed threshold and base flow approaches. Hydrograph corresponds to CEHQ station 40830 for the year 1996

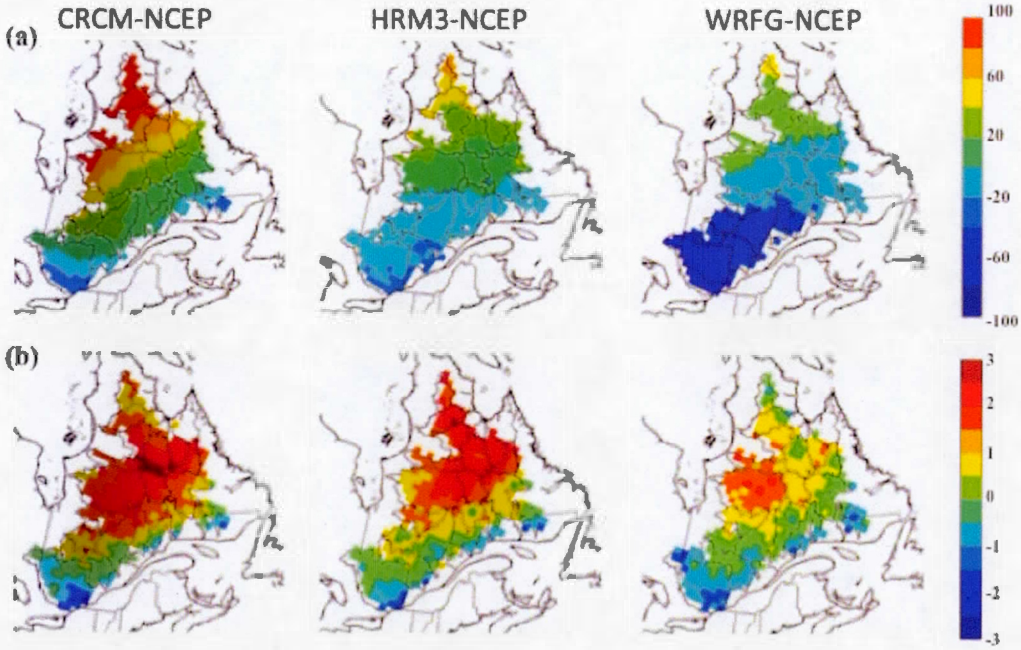


Figure 3. Biases in the (a) mean winter (DJF) snow water equivalent (in %) and (b) mean spring (MAM) 2-m temperature (in °C)

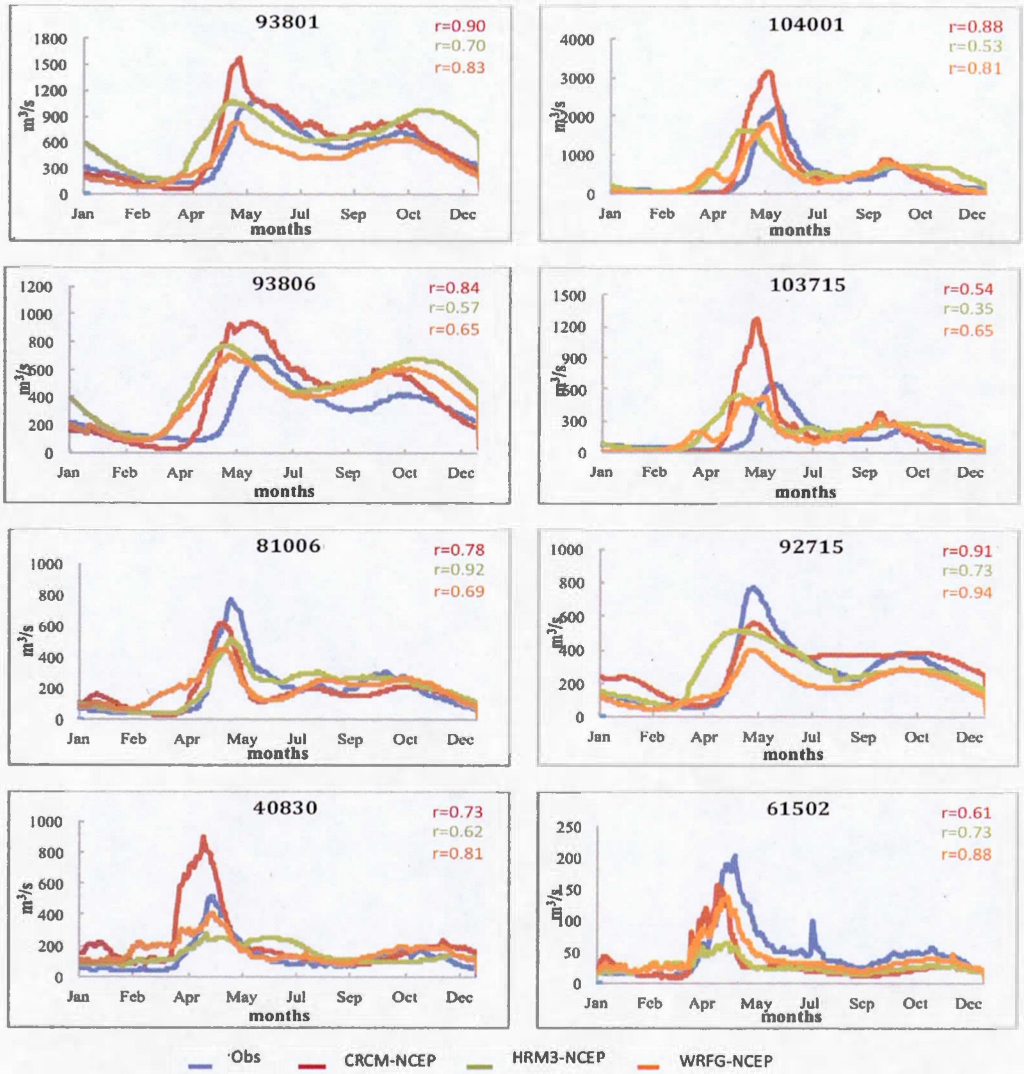
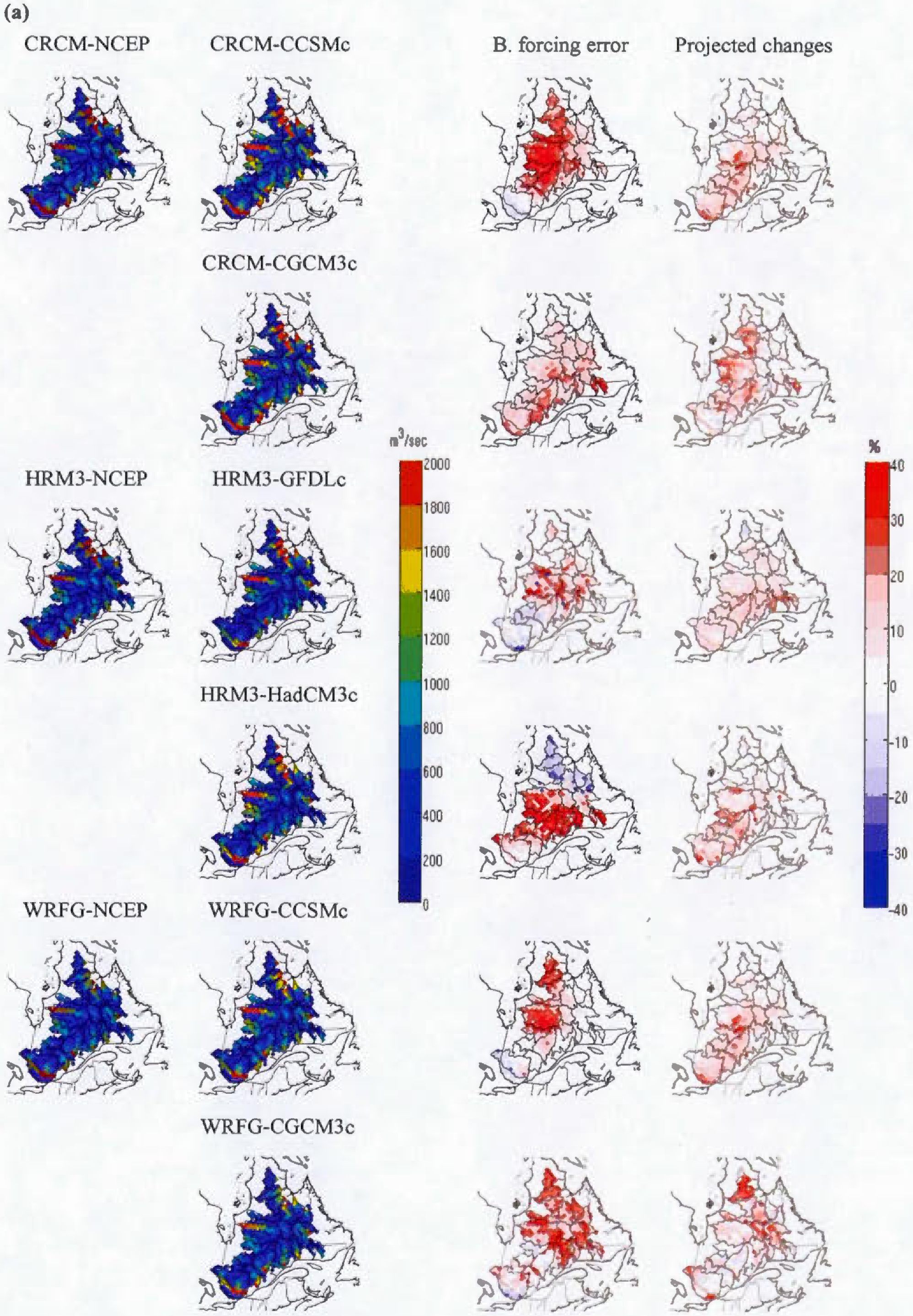
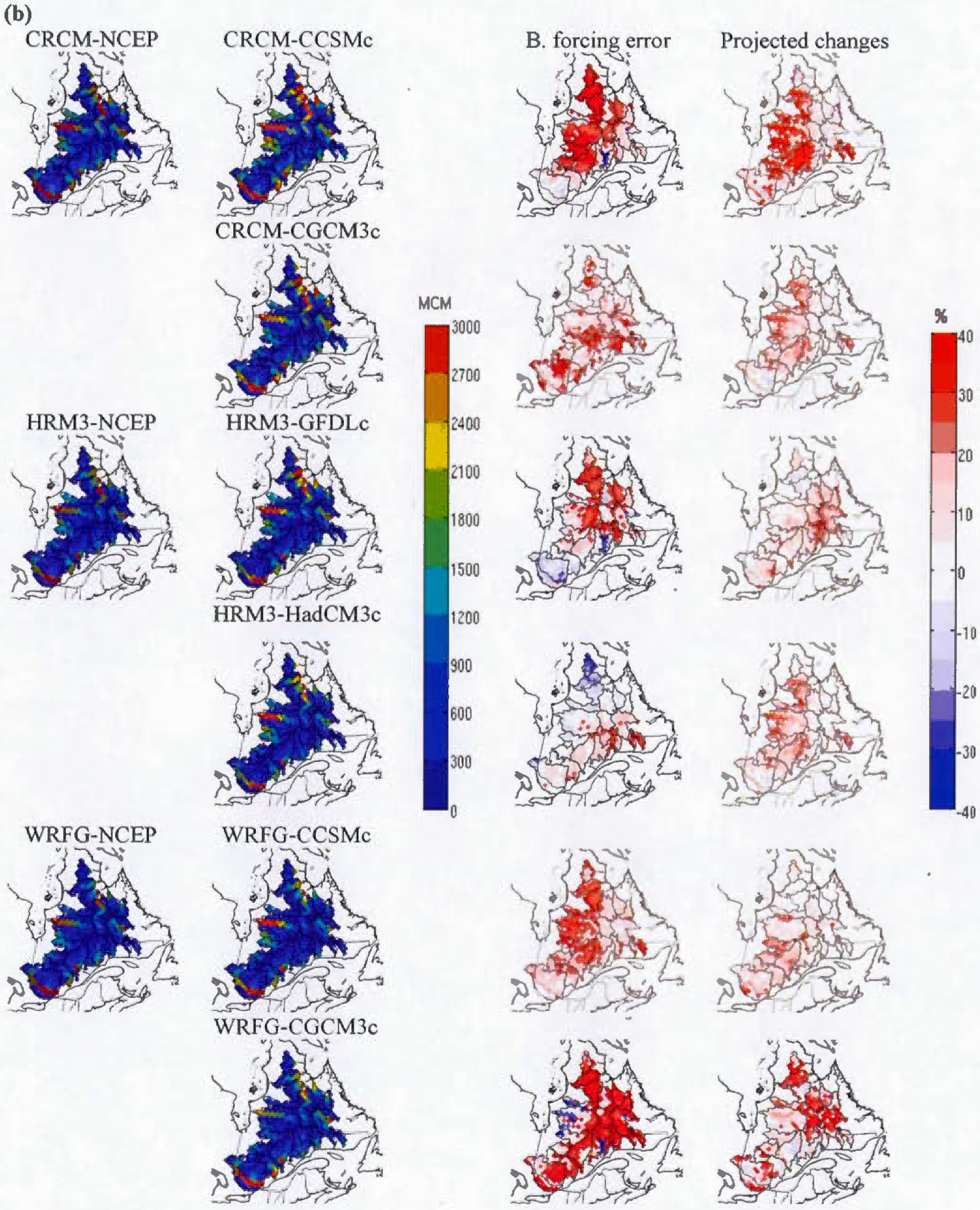


Figure 4. Comparison of observed and modelled hydrographs (mean daily streamflows). The length of the observed record varies from 10 to 20 years within the 1970–1999 period. The values of the correlation coefficient (r) based on mean daily streamflow comparisons and stations identification numbers are also shown.


(a)
CRCM-NCEP
CRCM-CCSMc
B. forcing error
Projected changes
CRCM-CGCM3c
HRM3-NCEP
HRM3-GFDLc
HRM3-HadCM3c
WRFG-NCEP
WRFG-CCSMc
WRFG-CGCM3c
m^3/sec
2000
1800
1600
1400
1200
1000
800
600
400
200
0
%
40
30
20
10
0
-10
-20
-30
-40


(b)
CRCM-NCEP
CRCM-CCSMc
B. forcing error
Projected changes
CRCM-CGCM3c
HRM3-NCEP
HRM3-GFDLc
HRM3-HadCM3c
WRFG-NCEP
WRFG-CCSMc
WRFG-CGCM3c
MCM
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
%
40
30
20
10
0
-10
-20
-30
-40

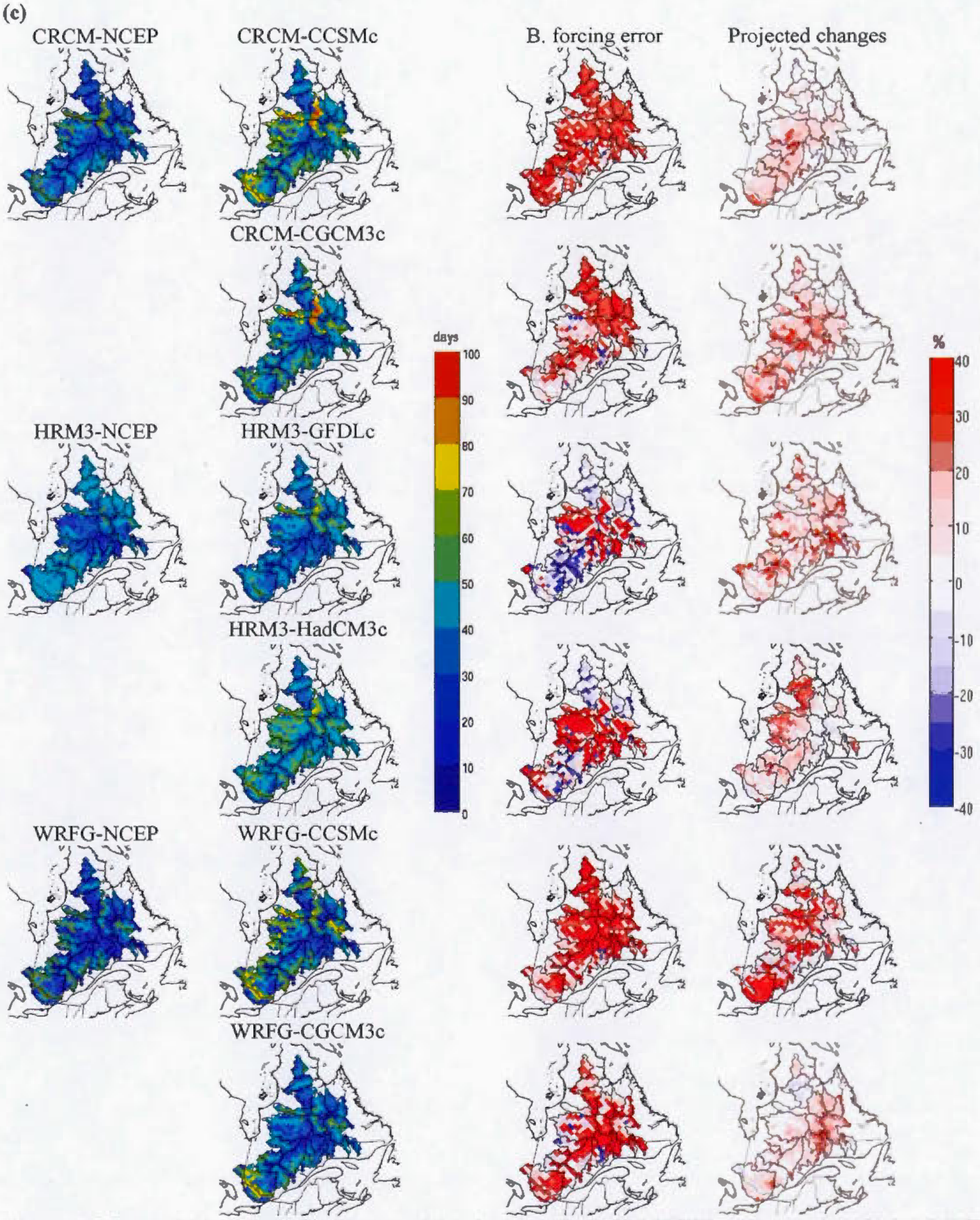
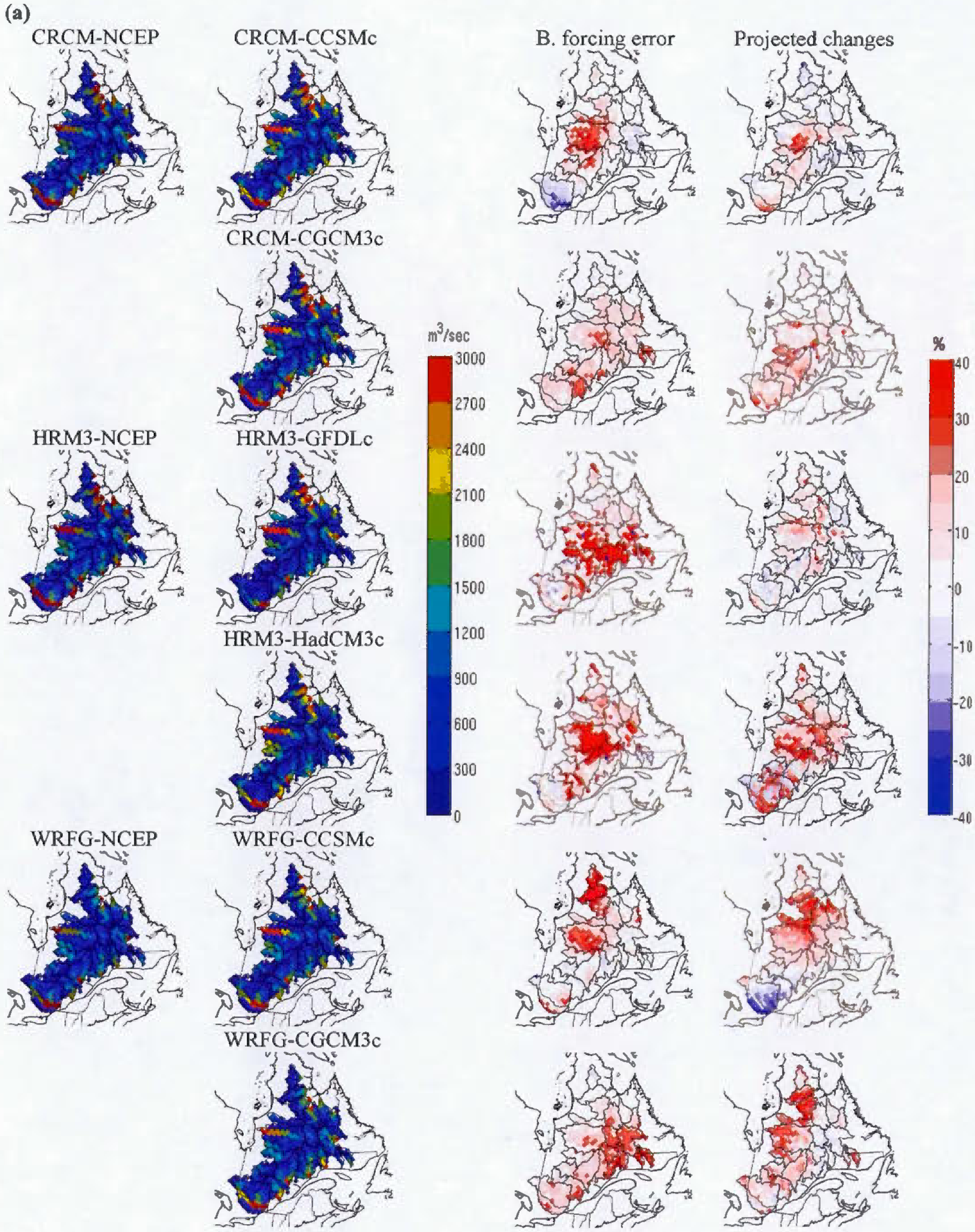
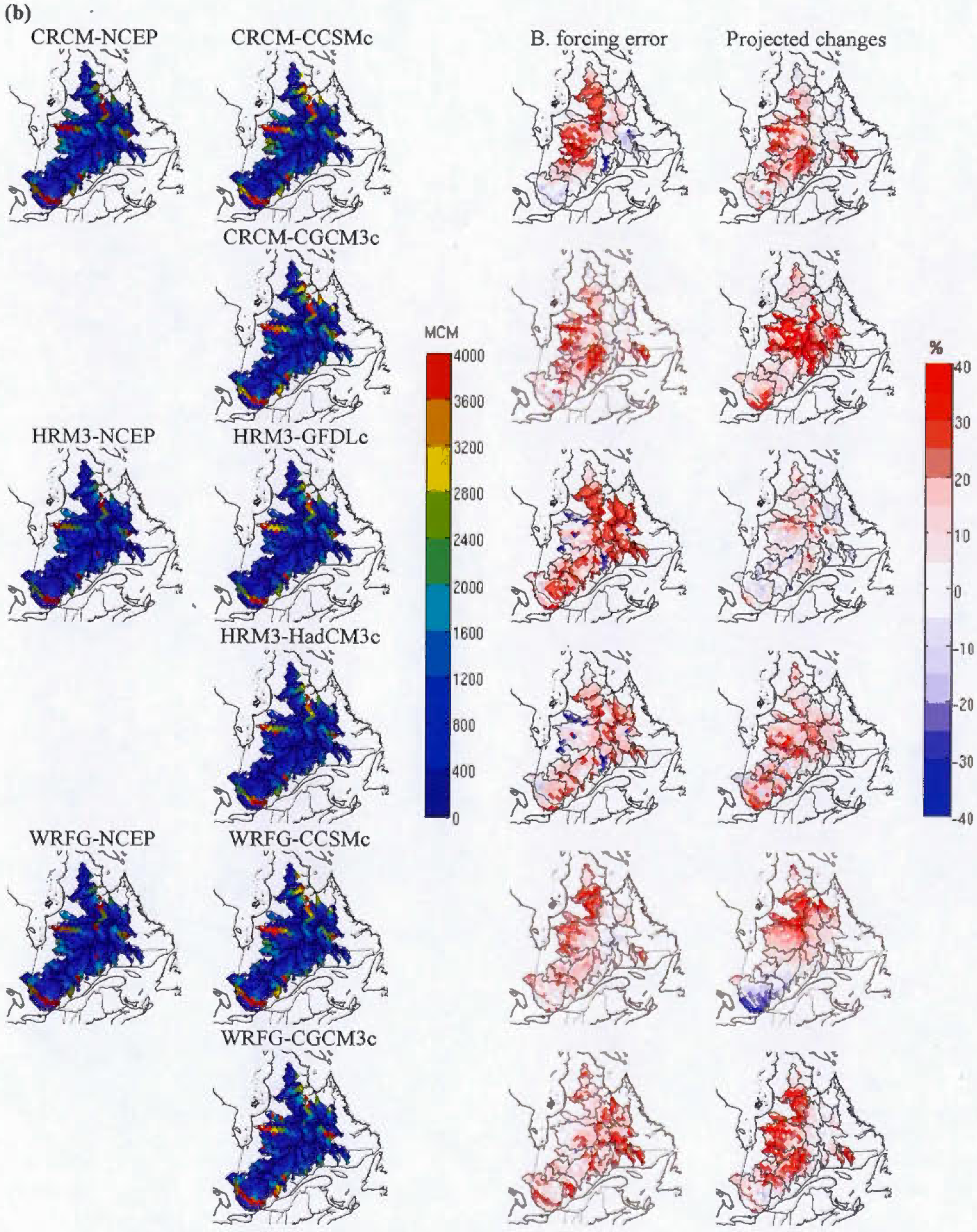


Figure.5: Mean of (a) peak, (b) volume and (c) duration for RCM-NCEP (column 1), RCM-AOGCMc (column 2) and boundary forcing errors (column 3). Projected change is shown in column 4.


(a)
CRCM-NCEP
CRCM-CCSMc
B. forcing error
Projected changes
CRCM-CGCM3c
HRM3-NCEP
HRM3-GFDLc
HRM3-HadCM3c
WRFG-NCEP
WRFG-CCSMc
WRFG-CGCM3c
m^3/sec
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
%
40
30
20
10
0
-10
-20
-30
-40


(b)
CRCM-NCEP
CRCM-CCSMc
B. forcing error
Projected changes
CRCM-CGCM3c
HRM3-NCEP
HRM3-GFDLc
HRM3-HadCM3c
WRFG-NCEP
WRFG-CCSMc
WRFG-CGCM3c
MCM
4000
3600
3200
2800
2400
2000
1600
1200
800
400
0
%
40
30
20
10
0
-10
-20
-30
-40

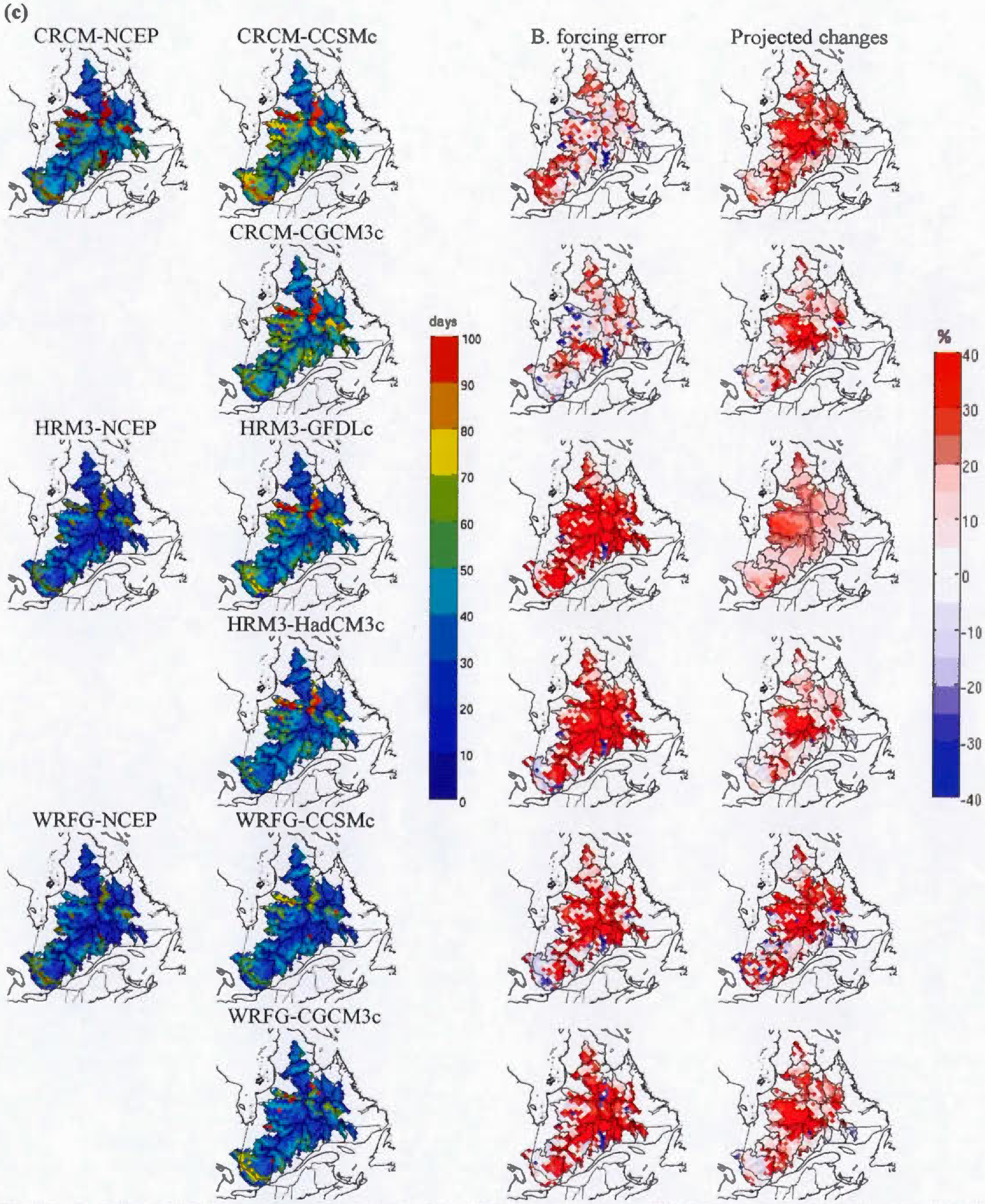
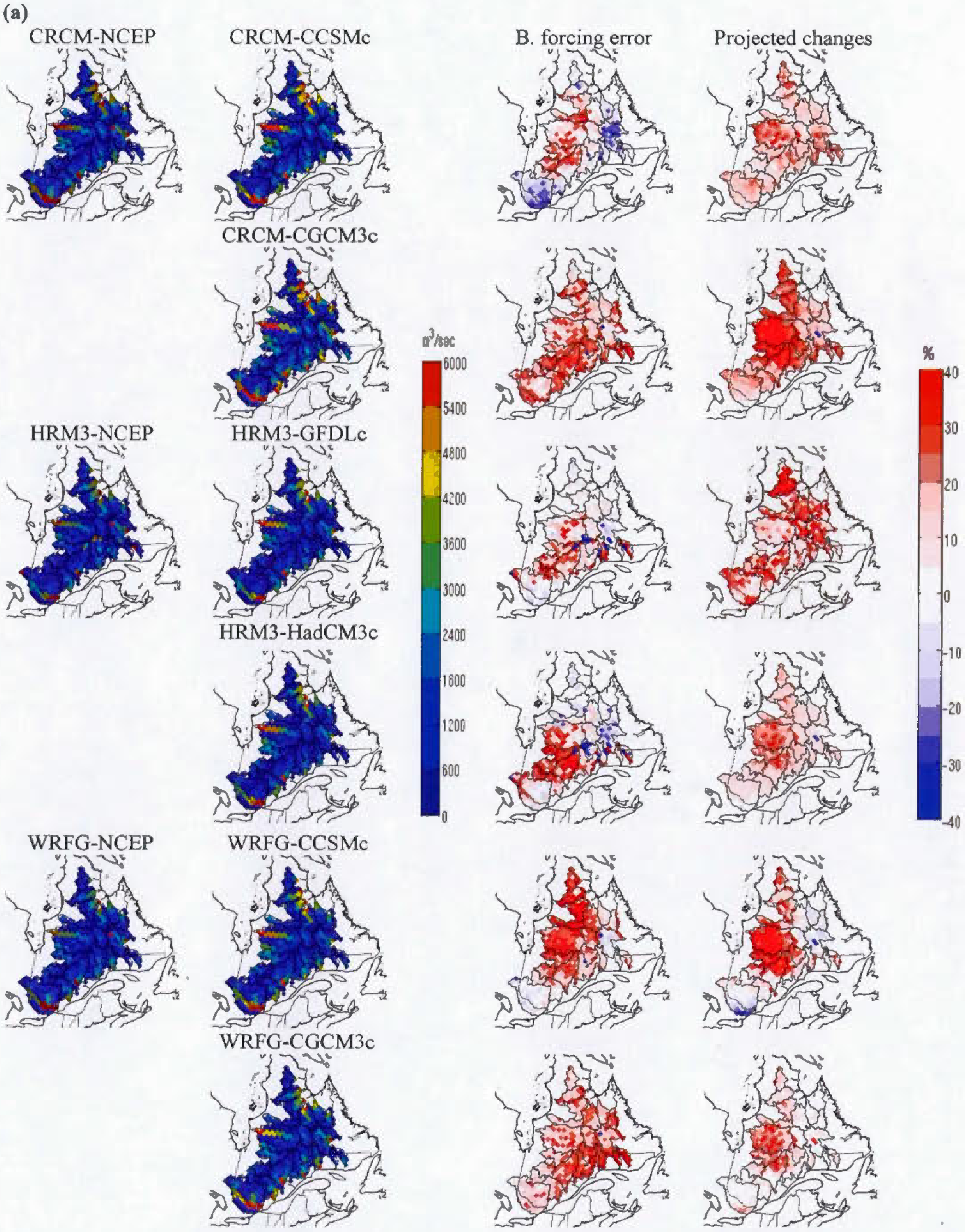
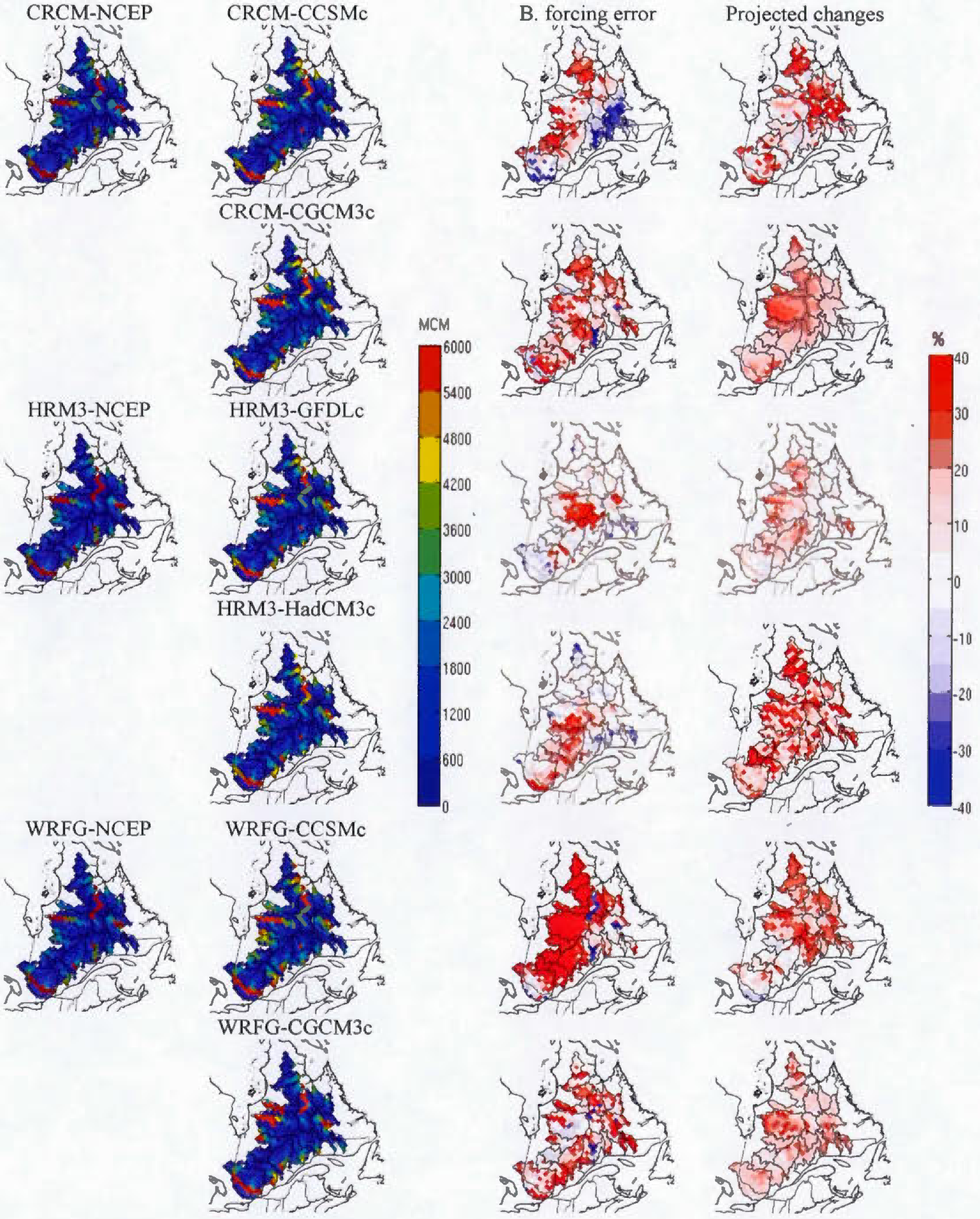


Figure.6: 5 year return level of (a) peak, (b) volume and (c) duration for RCM-NCEP (column 1), RCM-AOGCMc (column 2) and boundary forcing errors (column 3). Projected change is shown in column 4.


(a)
CRCM-NCEP
CRCM-CCSMc
B. forcing error
Projected changes
CRCM-CGCM3c
HRM3-NCEP
HRM3-GFDLc
HRM3-HadCM3c
WRFG-NCEP
WRFG-CCSMc
WRFG-CGCM3c
m³/sec
6000
5400
4800
4200
3600
3000
2400
1800
1200
600
0
%
40
30
20
10
0
-10
-20
-30
-40

(b)


CRCM-NCEP
CRCM-CCSMc
B. forcing error
Projected changes
CRCM-CGCM3c
HRM3-NCEP
HRM3-GFDLc
HRM3-HadCM3c
WRFG-NCEP
WRFG-CCSMc
WRFG-CGCM3c
MCM
6000
5400
4800
4200
3600
3000
2400
1800
1200
600
0
%
40
30
20
10
0
-10
-20
-30
-40

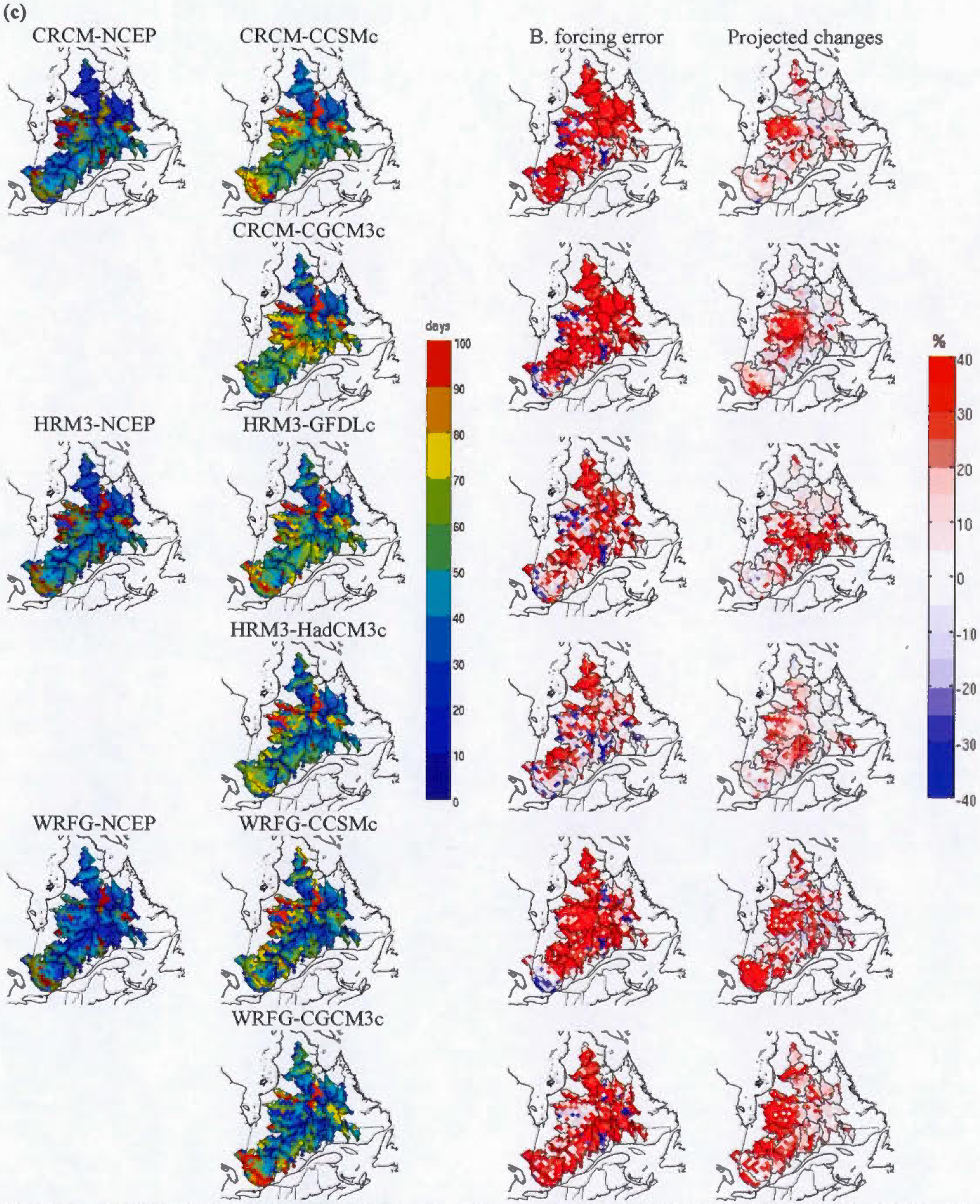
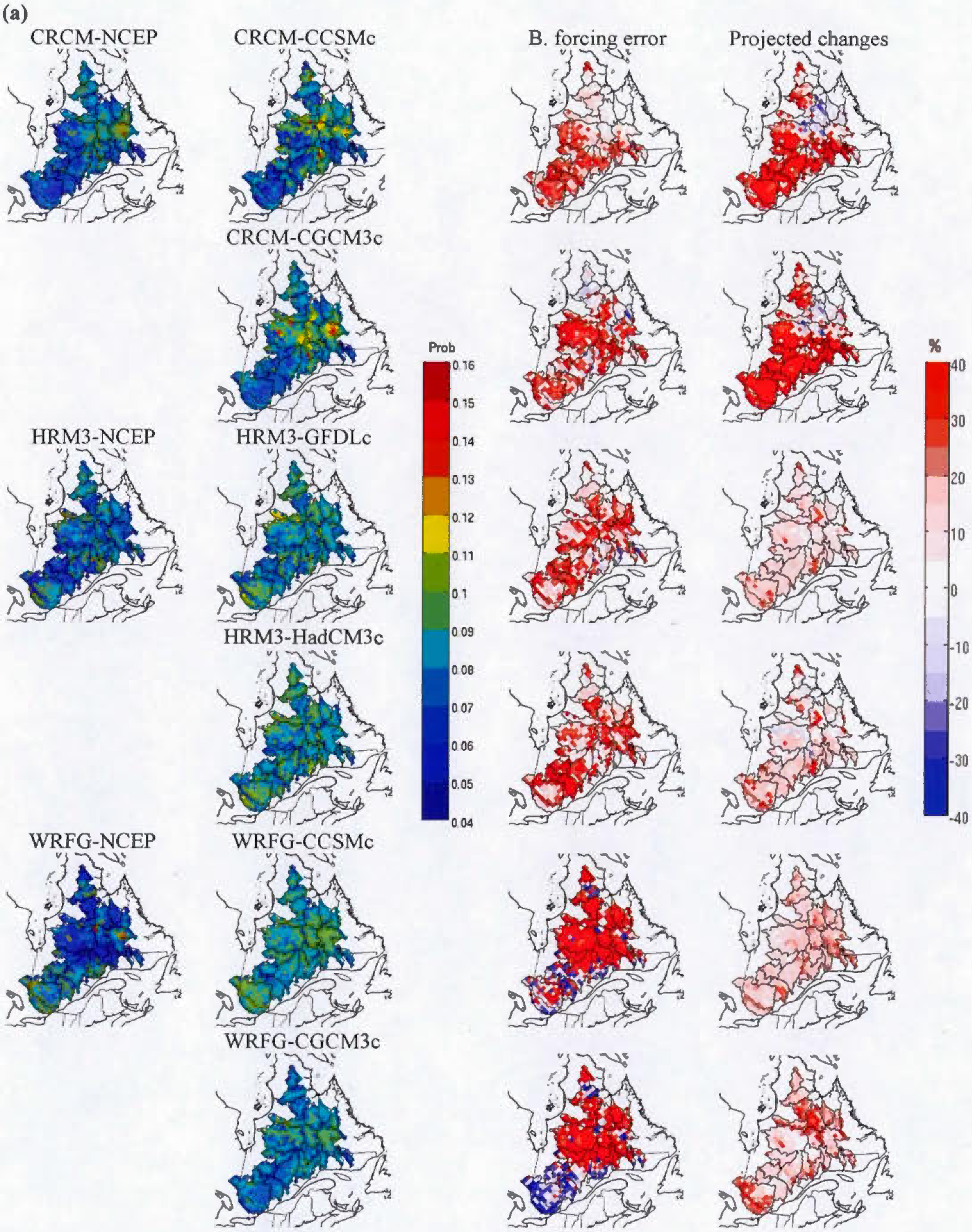
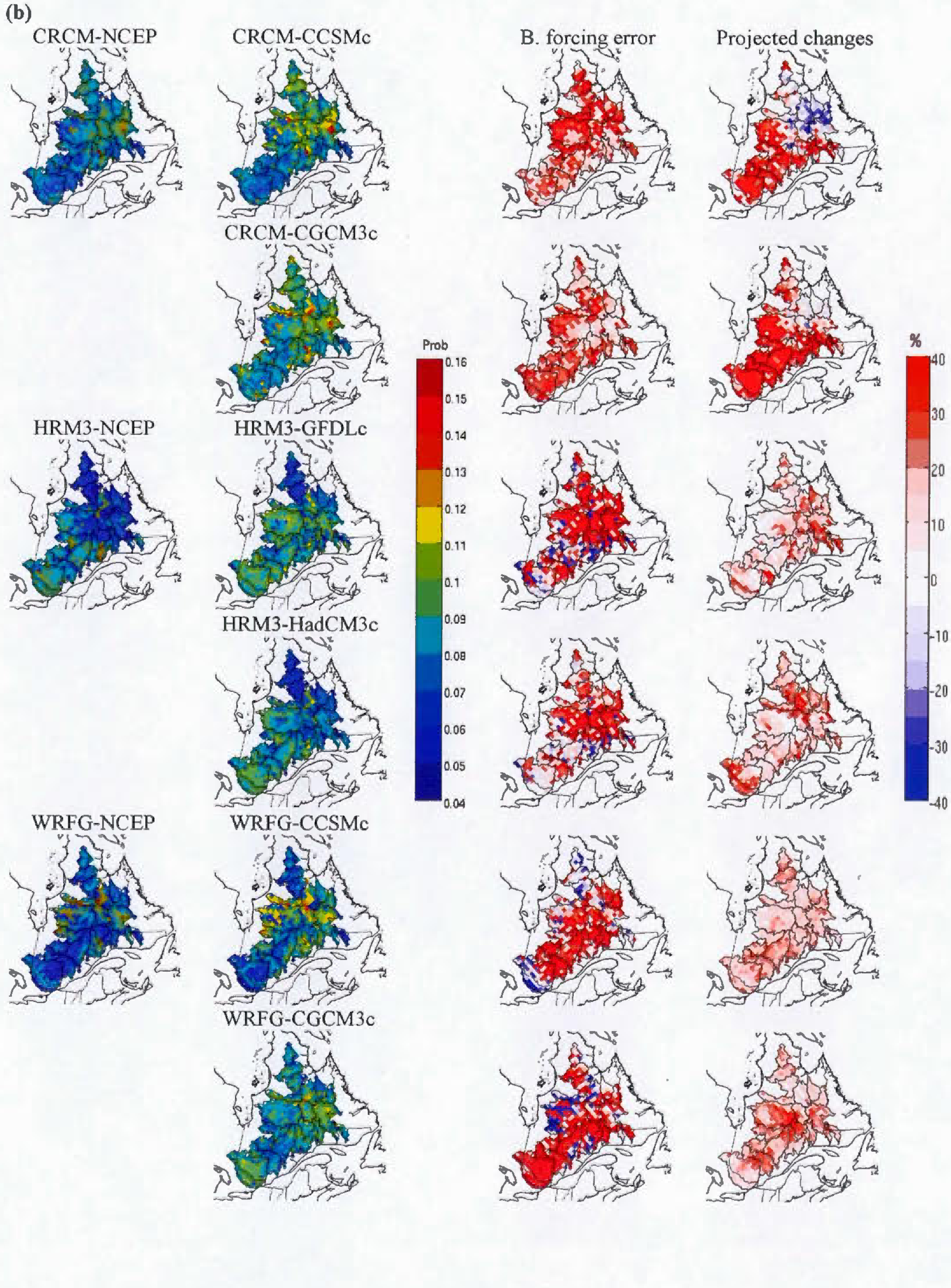


Figure.7: 30 year return level of (a) peak, (b) volume and (c) duration for RCM-NCEP (column 1), RCM-AOGCMc (column 2) and boundary forcing errors (column 3). Projected change is shown in column 4.


(a)
CRCM-NCEP
CRCM-CCSMc
B. forcing error
Projected changes
CRCM-CGCM3c
HRM3-NCEP
HRM3-GFDLc
HRM3-HadCM3c
WRFG-NCEP
WRFG-CCSMc
WRFG-CGCM3c
Prob
0.16
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
%
40
30
20
10
0
-10
-20
-30
-40


(b)
CRCM-NCEP
CRCM-CCSMc
B. forcing error
Projected changes
CRCM-CGCM3c
HRM3-NCEP
HRM3-GFDLc
HRM3-HadCM3c
WRFG-NCEP
WRFG-CCSMc
WRFG-CGCM3c
Prob
0.16
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
%
40
30
20
10
0
-10
-20
-30
-40

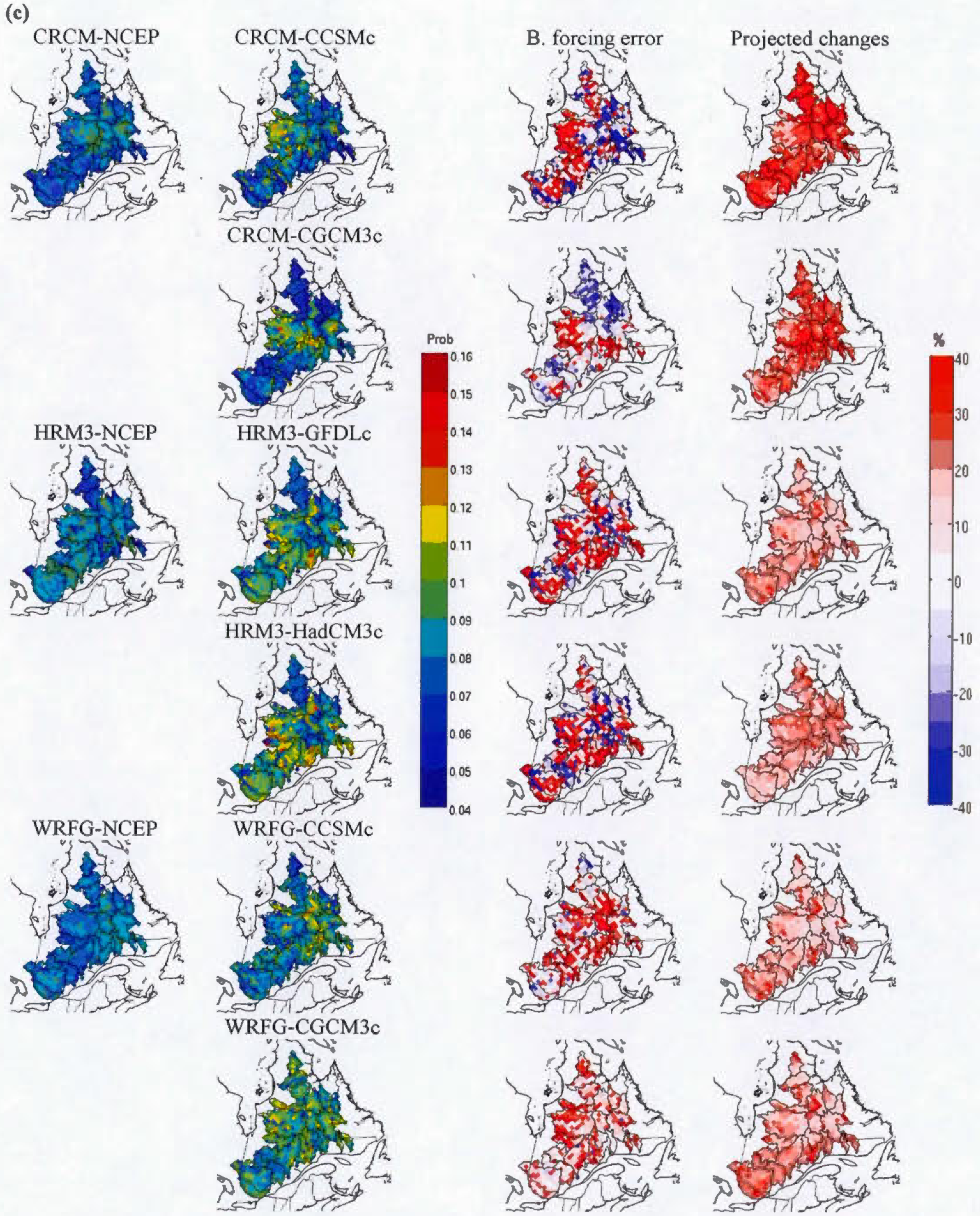
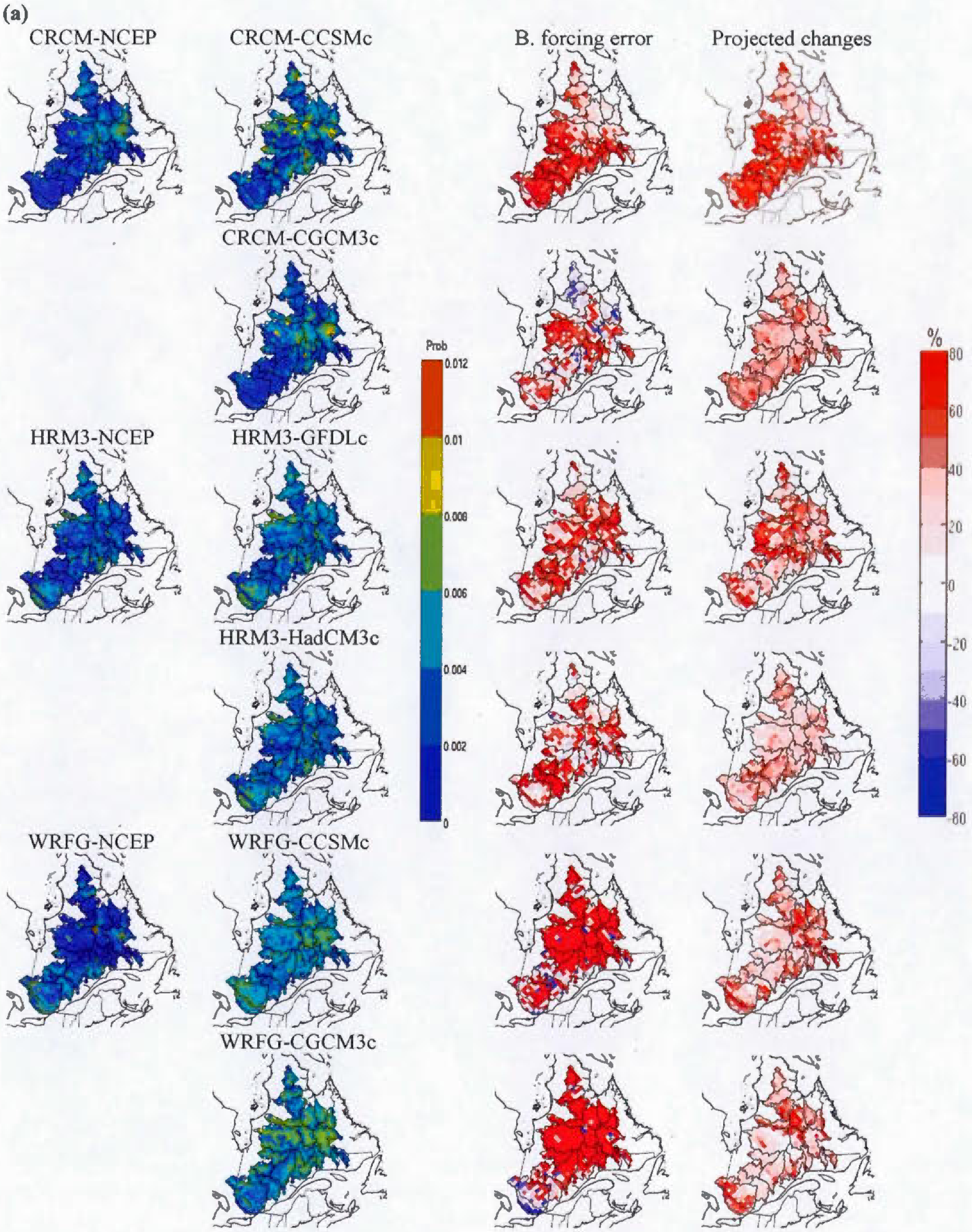
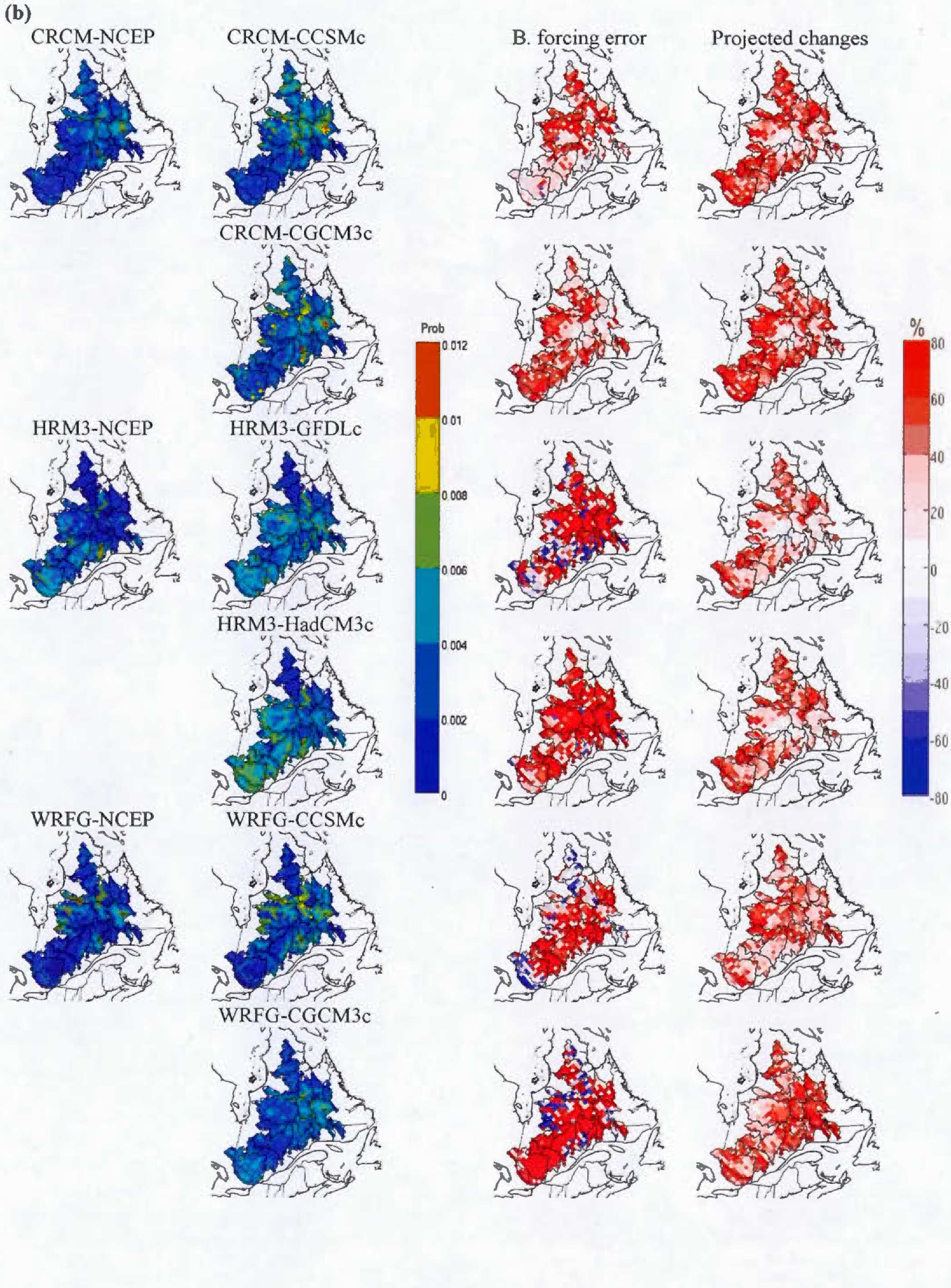


Figure.8: Joint occurrence probabilities for 5 year return level of (a) peak-volume, (b) peak-duration and (c) volume-duration for RCM-NCEP (column 1), RCM-AOGCMc (column 2) and boundary forcing errors (column 3). Projected change is shown in column 4.


(a)
CRCM-NCEP
CRCM-CCSMc
B. forcing error
Projected changes
CRCM-CGCM3c
HRM3-NCEP
HRM3-GFDLc
HRM3-HadCM3c
WRFG-NCEP
WRFG-CCSMc
WRFG-CGCM3c
Prob
0.012
0.01
0.008
0.006
0.004
0.002
0
%
80
60
40
20
0
-20
-40
-60
-80


(b)
CRCM-NCEP
CRCM-CCSMc
B. forcing error
Projected changes
CRCM-CGCM3c
HRM3-NCEP
HRM3-GFDLc
HRM3-HadCM3c
WRFG-NCEP
WRFG-CCSMc
WRFG-CGCM3c
Prob
0.012
0.01
0.008
0.006
0.004
0.002
0
%
80
60
40
20
0
-20
-40
-60
-80

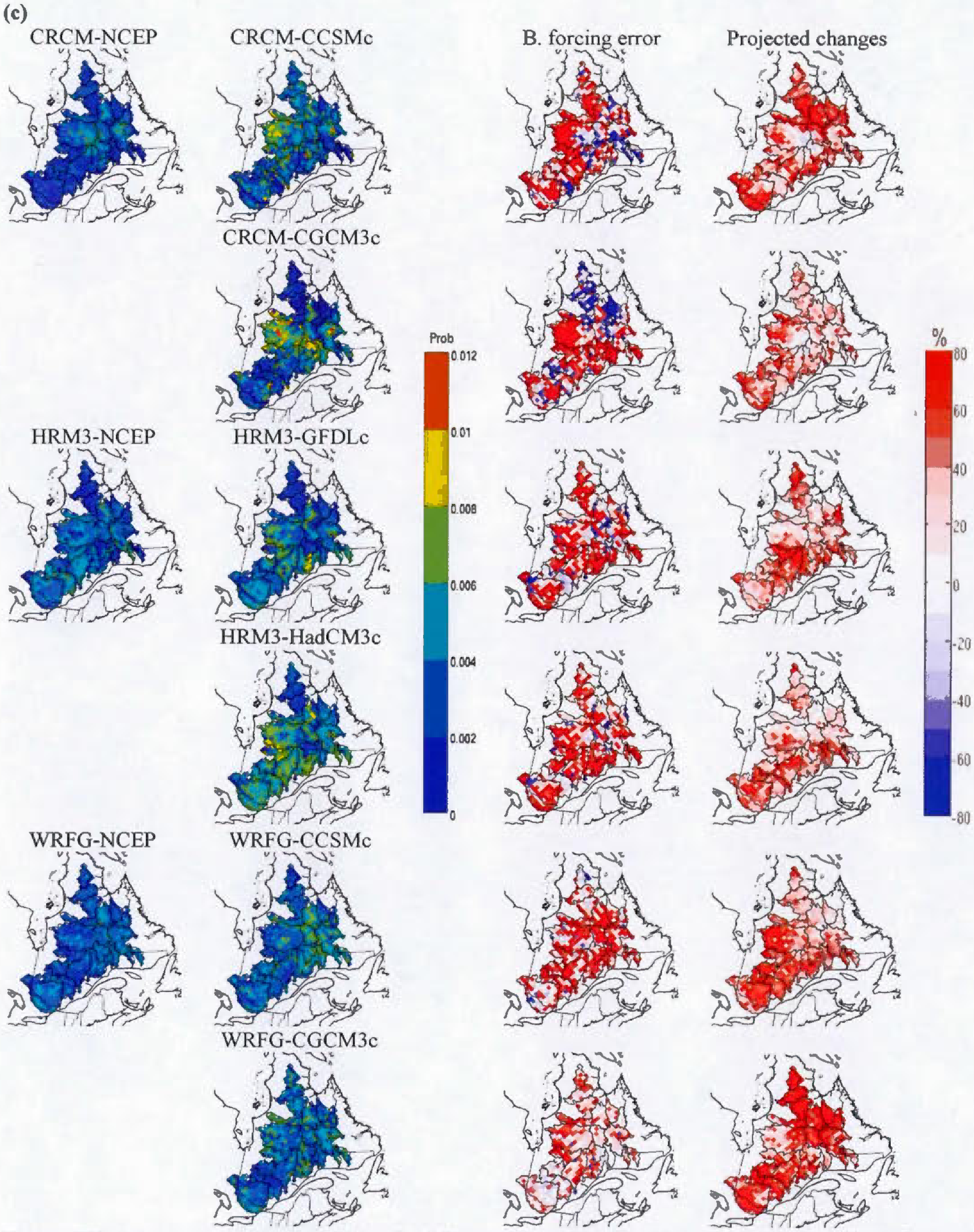


Figure.9: Joint occurrence probabilities for 30 year return levels of (a) peak-volume, (b) peak-duration and (c) volume-duration for RCM-NCEP (column 1), RCM-AOGCMc (column 2) and boundary forcing errors (column 3). Projected change is shown in column 4.

TABLEAUX

Table 1. Names and acronyms of six NARCCAP RCMs and details of AOGCM driven RCM simulations considered in this study

RCM		AOGCM Driven RCM simulations	
Name and modelling group	Acronym	Driving AOGCM	Simulation Acronym
Canadian Regional Climate Model (Ouranos)	CRCM	Canadian Global Climate Model, version 3: CGCM3	CRCM-CGCM3
		Community Climate Model, version 3: CCSM	CRCM-CCSM
Hadley Regional Model 3 (Hadley Centre)	HRM3	Hadley Centre Climate Model, version 3: HadCM3	HRM3-HadCM3
		Geophysical Fluid Dynamics Laboratory GCM: GFDL	HRM3-GFDL
Weather Research and Forecasting Model (Pacific Northwest National Laboratory)	WRFG	CGCM3	WRFG-CGCM3
		CCSM	WRFG-CCSM

Table 2. Information about selected CEHQ stations and representative reference grid points used in the comparison of flood characteristics derived from observed data, RCM-NCEP and RCM-AOGCMc for the period from 1970 to 1999.

CEHQ station						Reference grid point	
Station name	Station number	Longitude (W°)	Latitude (N°)	Basin area (Km^2)	Annual mean flow (m^3/s)	Longitude (W°)	Latitude (N°)
S1	40830	-75.8	47.1	6,84	126.5	-76.0	47.0
S2	61502	-72.0	48.4	2,28	49.1	-72.1	48.3
S3	81006	-72.9	51.1	7,28	190.4	-72.7	51.2
S4	92715	-74.5	53.2	13,2	263.6	-74.3	53.1
S5	93801	-76.9	55.2	33,9	365,3	-77.0	55.4
S6	93806	-74.0	54.8	21	327.9	-74.0	55.1
S7	103715	-68.6	56.6	8,99	164.2	-68.6	56.5
S8	104001	-67.6	57.9	29,472	504.5	-67.5	57.6

CHAPITRE III

CONCLUSION

Cette étude avait pour but d'estimer les changements appréhendés dans les trois caractéristiques (pic, volume et durée) des crues printanières (mars à juin) dans un contexte de changement climatique, pour 21 bassins versants situés principalement dans la province du Québec au Canada. Les changements appréhendés ont été analysés en utilisant trois modèles régionaux climatiques piloté chacun par deux modèles de circulation générale différents issus du projet NARCCAP. Une panoplie des données est aussi utilisée dans la validation des modèles provenant de CEHQ, CRU et Brown et al (2005). Ces données ont été moyennées et interpolées sur la grille de référence adopté dans la présente étude.

L'évaluation des impacts des changements climatiques sur les caractéristiques des crues a été effectuée sur une période de référence de 1971-2000 et une période de climat future visée de 2041-2070. Cette étude est abordée par une approche univariée basée sur la distribution marginale de chaque caractéristique et une autre multivariée dite Copula qui modélise la fonction de distribution conjointe de chaque pair des caractéristiques.

Afin d'évaluer la performance des MRC, les hydrogrammes simulés sont comparés aux ceux observés dans huit stations sélectionnées. Les moyennes, les niveaux de retour de 5- et 30- ans de chaque caractéristique ainsi que la probabilité conjointe d'occurrence des pairs, qui résultent de simulations MRCs pilotés par les données de ré-analyse NCEP, sont comparées à ceux issus de modèle MRC correspondant, piloté par un modèle de circulation générale afin de quantifier l'erreur due au forçage aux frontières par les modèles globaux. Au fur et à mesure, à chaque étape de cette analyse (c-à-d pour les moyennes, les niveaux de retour et la probabilité d'occurrence conjointe) une évaluation des changements appréhendés est faite en comparent les résultats obtenus pour le climat future (2041-2070) à ceux présents dans un climat de référence (1971-2000) en utilisant les six combinaisons de MRC-MCGA considérés dans cette étude.

La comparaison des hydrogrammes simulés par MRC piloté par NCEP et ceux obtenu à partir des observations de centre d'expertise en hydraulique du Québec pour les stations sélectionnées montre que la performance du modèle, dans la simulation de pic et sa pèriode d'occurence, dépend de la localisation géographique de chaque station. En effet, pour les stations situées dans le nord et le sud du Québec, le modèle canadien MRCC surestime les débits de pointe des crues par rapport aux données observées alors qu'il sousestime ce même paramètre dans les bassins versants situés au centre du domaine étudié. HRM3 et WRFG présentent des erreurs de performances négatives pour les stations du sud québécois.

L'évaluation des erreurs dues au forçage aux frontières est obtenue en comparant les caractéristiques des crues issues de simulations MRC pilotées par un MCGA avec celles issues de MRC-NCEP. Les résultats suggèrent diverses distributions spatiales des erreurs qui diffèrent selon les caractéristiques des crues, selon les différentes combinaisons MRC-MCGA et selon la localisation géographique des bassins fluviaux. En général, les CRCM-MCGAs et HRM3-MCGAs présentent les erreus les plus faibles par rapport à WRFG-MCGAs dans la simulation des trois caractéristiques.

Selon les résultats des comparaisons des moyennes des charactéristiques des crues et de l'analyse basée sur l'approche univariée, les basins versants de Sud sont associés aux faibles erreurs dues au choix du modèle de forçage aux frontières. En général, la durée d'inondation est le paramètre le plus difficile à simuler vu qu'elle est toujours associée aux importantes valeurs d'erreurs par rapport au pic et au volume de crue. Il est à noter que les erreurs dues aux forçage aux frontières associés aux analyses de niveau de retour de 30 ans sont généralement plus importantes que celles pour le niveau de retour de 5 ans

Sur la base de la comparaison des simulations du climat actuel et future, une augmentation des valeurs moyennes des trois caractéristiques des crues printanières est prévue pour la plupart des bassins versants considérés dans cette étude. Il est important de mentionner que certaines différences ont été notées entre les bassins et entre les différentes combinaisons des modèles. Ceci est principalement du au choix de modèle MCGA pour le forçage aux frontières et/ou au paramétrage physique et dynamique des modèles.

Les changements appréhendés des niveaux de retour de 5 et de 30 ans des trois caractéristiques des crues printanières ont été calculés et les résultats annoncent une augmentation dans le climat future des différents niveaux de retour pour la majorité des bassins versants considérés dans cette étude. Ces résultats sont en cohérence avec les résultats de Huziy et al. (2012) et Clavet-Gaumont (2012) pour les pics des crues et avec l'étude faite par Jeong et al. (2014) qui a prouvé une augmentation pour les trois caractéristiques des crues pour la même période du climat future sur les mêmes 21 bassins versants.

Pour la première fois, et dans cette étude, les prévisions des changements appréhendés de la probabilité d'occurrence conjointe P des trois paires de caractéristiques des crues (c.-à-d pic-volume, pic-durée et le volume-durée) à l'aide de trois MRC du NARCCAP pour le climat actuel (1971-2000) et celui future (2041-2070) pilotés par quatre conditions initiales MCGA ont été étudiés pour les 21 bassins versants du Québec. Les résultats dénotent une importante disparité entre les simulations des différentes combinaisons des modèles MRC. Les projections prévoient une augmentation future de P pour la majorité des points de grille du domaine étudié. Ces augmentations sont plus importantes pour les caractéristiques liées au long niveau de retour (30 ans) que celles prévues pour le niveau de retour de 5 ans.

Les résultats de cette étude sont très importants et utiles pour soutenir la bonne gestion et l'élaboration des stratégies d'adaptation dans des nombreux secteurs, en particulier le secteur de l'énergie . Bien que les incertitudes des modèle sont prises en considérations dans cette étude, en utilisant 6 combinaisons MRC-MCGA, l'évaluation des impacts des changement climatiques sur les caractéristiques des crues est limitée seulement à la province du Québec et seulement au scénario d'émissions SRES A2. Une évaluation plus complète des risques d'inondation impliquerait un domaine d'étude plus large que celui considéré dans cette étude ainsi que l'utilisation des plusieurs scenarios d'émissions est également nécessaire pour évaluer correctement les incertitudes dans les projections futures des caractéristiques des crues.

RÉFERENCES

Aissia, M. A. B., Chebana, F., Ouarda, T. B. M. J., Roy, L., Desrochers, G., Chartier, I., & Robichaud, É. (2012). Multivariate analysis of flood characteristics in a climate change context of the watershed of the Baskatong reservoir, Province of Québec, Canada. Hydrological Processes, 26(1), 130-142.

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. Nature, 438(7066), 303-309.

Booij, M. J. (2005). Impact of climate change on river flooding assessed with different spatial model resolutions. Journal of hydrology, 303(1), 176-198.

Bosshard, T., Kotlarski, S., Zappa, M., & Schär, C. (2014). Hydrological Climate-Impact Projections for the Rhine River: GCM–RCM Uncertainty and Separate Temperature and Precipitation Effects*. Journal of Hydrometeorology, 15(2), 697-713.

Brown, R. D., & Robinson, D. A. (2011). Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty. The Cryosphere, 5(1), 219-229.

Brutel-Vuilmet, C., Ménégoz, M., & Krinner, G. (2013). An analysis of present and future seasonal Northern Hemisphere land snow cover simulated by CMIP5 coupled climate models. The Cryosphere, 7(1), 67.

Cahill, A. T. (2011, December). Copula approaches to the relationship between extreme rainfall and extreme flow. In AGU Fall Meeting Abstracts (Vol. 1, p. 1041).

Cao, S., Lee, K. T., Ho, J., Liu, X., Huang, E., & Yang, K. (2010). Analysis of runoff in ungauged mountain watersheds in Sichuan, China using kinematic-wave-based GIUH model. Journal of Mountain Science, 7(2), 157-166.

Charlton, R., Fealy, R., Moore, S., Sweeney, J., & Murphy, C. (2012). Assessing the Impact of Climate Change on Water Supply and Flood Hazard in Ireland using Statistical Downscaling and Hydrological Modelling Technique.

Chebana, F., & Ouarda, T. B. (2011). Multivariate quantiles in hydrological frequency analysis. Environmetrics, 22(1), 63-78.

Chowdhary, H., & Singh, V. P. (2010). Reducing uncertainty in estimates of frequency distribution parameters using composite likelihood approach and copula-based bivariate distributions. Water Resources Research, 46(11).

Christensen JH., Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magana Rueda V, Mearns L, Menéndez CG, Raisanen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Clavet-Gaumont, J., Sushama, L., Khaliq, M. N., Huziy, O., & Roy, R. (2013). Canadian RCM projected changes to high flows for Québec watersheds using regional frequency analysis. International Journal of Climatology, 33(14), 2940-2955.

Dibike, Y. B., & Coulibaly, P. (2007). Validation of hydrological models for climate scenario simulation: the case of Saguenay watershed in Quebec. Hydrological Processes, 21(23), 3123-3135.

Dufresne, J. L., Foujols, M. A., Denvil, S., Caubel, A., Marti, O., Aumont, O., ... & Mignot, J. (2013). Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. Climate Dynamics, 40(9-10), 2123-2165.

Genest, C., & Favre, A. C. (2007). Everything you always wanted to know about copula modeling but were afraid to ask. Journal of hydrologic engineering, 12(4), 347-368.

Gosling, S., Taylor, R. G., Arnell, N., & Todd, M. C. (2011). A comparative analysis of projected impacts of climate change on river runoff from global and catchment-scale hydrological models. Hydrology and Earth System Sciences, 15(1), 279-294.

Hanna, E., Huybrechts, P., Steffen, K., Cappelen, J., Huff, R., Shuman, C., ... & Griffiths, M. (2008). Increased runoff from melt from the Greenland Ice Sheet: a response to global warming. Journal of Climate, 21(2), 331-341.

Huziy, O., Sushama, L., Khaliq, M. N., Laprise, R., Lehner, B., & Roy, R. (2013). Analysis of streamflow characteristics over Northeastern Canada in a changing climate. Climate Dynamics, 40(7-8), 1879-1901..

IPCC (2013) In: Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner, 2013: Long-term climate change: Projections, commitments and irreversibility. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Doschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, 1029-1136, doi:10.1017/CBO9781107415324.024.

Jeong, D. I., Sushama, L., Khaliq, M. N., & Roy, R. (2014). A copula-based multivariate analysis of Canadian RCM projected changes to flood characteristics for northeastern Canada. Climate Dynamics, 42(7-8), 2045-2066.

Jiang, C., Xiong, L., Xu, C. Y., & Guo, S. (2015). Bivariate frequency analysis of nonstationary low-flow series based on the time-varying copula. Hydrological Processes, 29(6), 1521-1534.

Karmakar, S., & Simonovic, S. P. (2008). Bivariate flood frequency analysis: Part 1. Determination of marginals by parametric and nonparametric techniques. Journal of Flood Risk Management, 1(4), 190-200.

Karmakar S, Simonovic SP (2009) Bivariate flood frequency analysis. Part 2: a copula-based approach with mixed marginal distribu- tions. J Flood Risk Manage 2:32–44

Khaliq, M. N., Sushama, L., Monette, A., & Wheater, H. (2015). Seasonal and extreme precipitation characteristics for the watersheds of the Canadian Prairie Provinces as simulated by the NARCCAP multi-RCM ensemble. Climate Dynamics, 44(1-2), 255-277.

Kharin, V. V., Zwiers, F. W., Zhang, X., & Wehner, M. (2013). Changes in temperature and precipitation extremes in the CMIP5 ensemble. Climatic Change, 119(2), 345-357.

Kwak, J. W., Kim, Y. S., Lee, J. S., & Kim, H. S. (2012). Analysis of drought characteristics using copula theory. In Proceedings of the World Environmental and Water Resources Congress (pp. 1762-1771).

Lehner, B., Verdin, K., & Jarvis, A. (2008). New global hydrography derived from spaceborne elevation data. EOS, Transactions American Geophysical Union, 89(10), 93-94.

Mailhot, A., Panthou, G., & Talbot, G. (2014). Recommandations sur les majorationsa considérer pour les courbes Intensité-Durée-Fréquence (IDF) aux horizons 2040-2070 et 2070-2100 pour l'ensemble du Québec PHASE II.

Mareuil A, Leconte R, Brissette F, Minville M (2007) Impact of climate change on the frequency and severity of floods in the Chateauguay River basin, Québec. Canadian Journal of Civil Engineering 34:1048-1060.

Mearns, L. O., Gutowski, W., Jones, R., Leung, R., McGinnis, S., Nunes, A., & Qian, Y. (2009). A regional climate change assessment program for North America. Eos, Transactions American Geophysical Union, 90(36), 311-311.

Mearns, L. O., Sain, S., Leung, L. R., Bukovsky, M. S., McGinnis, S., Biner, S., ... & Sloan, L. (2013). Climate change projections of the North American regional climate change assessment program (NARCCAP). Climatic Change, 120(4), 965-975.

Minville, M., Brissette, F., & Leconte, R. (2008). Uncertainty of the impact of climate change on the hydrology of a nordic watershed. Journal of hydrology, 358(1), 70-83.

Mladjic, B., Sushama, L., Khaliq, M. N., Laprise, R., Caya, D., & Roy, R. (2011). Canadian RCM projected changes to extreme precipitation characteristics over Canada. Journal of Climate, 24(10), 2565-2584.

Monette, A., Sushama, L., Khaliq, M. N., Laprise, R., & Roy, R. (2012). Projected changes to precipitation extremes for northeast Canadian watersheds using a multi-RCM ensemble. Journal of Geophysical Research: Atmospheres (1984–2012), 117(D13).

Orlowsky, B., & Seneviratne, S. Global changes in extreme events from multi-model GCM ensembles: Regional and seasonal dimension.

Parent, E., Favre, A. C., Bernier, J., & Perreault, L. (2014). Copula models for frequency analysis what can be learned from a Bayesian perspective?. Advances in Water Resources, 63, 91-103.

Poitras, V., Sushama, L., Seglenieks, F., Khaliq, M. N., & Soulis, E. (2011). Projected changes to streamflow characteristics over western Canada as simulated by the Canadian RCM. Journal of Hydrometeorology, 12(6), 1395-1413.

Quilbé, R., Rousseau, A. N., Moquet, J. S., Savary, S., Ricard, S., & Garbouj, M. S. (2008). Hydrological responses of a watershed to historical land use evolution and future land use scenarios under climate change conditions. Hydrology and Earth System Sciences Discussions, 12(1), 101-110.

Saad, C., St-Hilaire, A., Gachon, P., & El Adlouni, S. (2015). The 2011 flood event in the Richelieu River basin: Causes, assessment and damages. Canadian Water Resources Journal/Revue canadienne des ressources hydriques, (ahead-of-print), 1-10.

Song, S., & Singh, V. P. (2010). Frequency analysis of droughts using the Plackett copula and parameter estimation by genetic algorithm. Stochastic Environmental Research and Risk Assessment, 24(5), 783-805.

Stocker, T. F., et al. "Technical summary." Climate Change (2013): The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2013. 33-115.

Sushama L, Laprise R, Caya D, Frigon A, Slivitzky M (2006) Canadian RCM projected climatechange signal and its sensitivity to model errors. Int J Climatol 26:2141–2159

Teutschbein, C., & Seibert, J. (2012). Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. Journal of Hydrology, 456, 12-29.

Thiémonge, N., & Clavet-Gaumont, J. (2015). Impacts des changements climatiques sur les volumes de crues printanières de la Côte-Nord du Québec. Canadian Water Resources Journal/Revue canadienne des ressources hydriques, (ahead-of-print), 1-12.

Tian, Y., Xu, Y. P., & Zhang, X. J. (2013). Assessment of climate change impacts on river high flows through comparative use of GR4J, HBV and Xinanjiang models. Water resources management, 27(8), 2871-2888.

Tong, X., Wang, D., Singh, V. P., Wu, J. C., Chen, X., & Chen, Y. F. (2014). Impact of Data Length on the Uncertainty of Hydrological Copula Modeling. Journal of Hydrologic Engineering.

Wehner, M. F., Smith, R. L., Bala, G., & Duffy, P. (2010). The effect of horizontal resolution on simulation of very extreme US precipitation events in a global atmosphere model. Climate dynamics, 34(2-3), 241-247.

Zhang Q, Li J, Singh VP, Xu C-Y (2012) Copula-based spatio-temporal patterns of precipitation extremes in China. International Journal of Climatology doi:10.1002/joc.3499.