Differences in the Potential Hydrologic Impact of Climate Change to the Athabasca and Fraser River Basins of Canada with and without Considering Shifts in Vegetation Patterns Induced by Climate Change

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ABSTRACT

The research objectives are to estimate differences between the potential impact of climatic change to the Athabasca River basin (ARB) and Fraser River basin (FRB) of Canada with and without considering shifts in vegetation patterns induced by climate change and how much the difference will depend on vegetation types and climate. The hydrologic effects of vegetation shifts on ARB and FRB were estimated by applying the Mapped Atmosphere–Plant–Soil System (MAPSS) simulated results based on the Intergovernmental Panel on Climate Change's First and Second Assessment Report general circulation model (GCM) scenarios to the modified Interaction Soil–Biosphere–Atmosphere (MISBA) scheme. According to MAPSS, vegetation shifts in mountainous regions of FRB are expected to be dominated by conifer/broadleaf competition, while in ARB, climate projections of MAPSS predicted a southern expansion of the boreal forest. Because of differences in sublimation, there is a tendency for more snow to accumulate in open grassland than forests. Furthermore, changes to simulated mean annual maximum snowpack, runoff, and basin area covered by grassland are positively correlated to each other. Generally, a 4% increase in snow water equivalent (SWE) results in a 1% increase in mean annual runoff. These relationships hold true in both basins over a wide range of GCM-projected climate conditions and vegetation responses, suggesting that most changes in mean annual flow can be attributed to changes in SWE. Because of the different modeling approaches between MAPSS and MISBA, it seems that the treatment of these processes in vegetation and hydrologic models should be similar before conclusions can be drawn from various stand-alone simulations. Ideally, a land surface scheme should be coupled with a vegetation model in future studies.

1. Introduction

Energy and mass transfer feedbacks between the earth’s ecosystem and the atmosphere, ocean, and land surface systems have long been recognized as having impacts on future projections of climatic change, and given sufficient time, climate change induced by increasing greenhouse gases in the atmosphere is expected to change the global distribution of terrestrial vegetation. Through the First (FAR), Second (SAR), Third (TAR), and Fourth Assessment Reports (AR4) of the Intergovernmental Panel on Climate Change (IPCC), atmospheric general circulation models (GCMs) were run to equilibrium under transient forcing scenarios of a variety of greenhouse gases, including doubled CO₂ forcings with fixed land and ocean properties (Houghton 1990, 1996, 2001; Solomon et al. 2007), even though in TAR and AR4 there was the addition of increasingly complex soil–vegetation–atmosphere transfer (SVAT) schemes that can dynamically model energy and mass transfers between the atmosphere and the land surface. However, dynamic general vegetation models (DGVMs), which would allow for the inclusion of the effect of ecological dynamics (Woodward et al. 1995; Foley et al. 1996; Stich et al. 2003), generally lag behind the development of GCMs, and that was likely why DGVMs were not coupled to GCMs in FAR, SAR, TAR, and AR4. DGVMs are transient vegetation models in which competition between various plant life in different environments is simulated based on ecological constraints.

In general, the analysis of vegetation migration in response to climate change is usually based on biogeographical classifications and the hypothesis of dynamic
equilibrium (the rate of climate change is comparable to the rate of vegetation response), which assumes that flora in any location are predetermined by climate parameters, such as forest gap models (Bugmann et al. 2001) that simulate vegetation mortality in relation to climate change or variability.

Species change can result from subdominant species replacing previously dominant species or by species migration. Ecosystem simulations under future climate scenarios have suggested the long-term equilibrium ranges of many species could shift an order of magnitude faster than after the last glaciation environment (Neilson et al. 2005). Species that cannot migrate fast enough to keep up with these changes could potentially die off. However, the development of migration models has not adequately addressed triggering mechanisms for catastrophic fires, insect infestations, and the different migration rates of plant species with similar ecological functions (Neilson et al. 2005).

Ecological dynamics influence future climate by altering the distribution of vegetation species on the land surface, which in turn changes the rates of water and energy transfers via changes in surface albedo, surface roughness, and transpiration rates. For example, a northern shift in forest coverage would bring about significant carbon sequestration (negative temperature feedback), a decrease in albedo (positive temperature feedback), and an increase in surface roughness, potentially resulting in a shift from sensible to latent heat fluxes (negative temperature feedback) and a potential increase in cloud cover due to increased transpiration (positive or negative temperature feedback, depending on cloud type) (Peng 2000; Neilson et al. 2005). All these climate feedbacks related to vegetation dynamics should affect hydrologic responses to climate change.

The Mapped Atmosphere–Plant–Soil System (MAPSS) model is a steady-state, nontransient, static biogeographical model developed by Neilson (1995) that can simulate the thermal and water balance constraints that act on individual plant types (e.g., trees, shrubs, and grasses) and biome physiognomy (e.g., forest and savannas). MAPSS has been the basis of a variety of climate change studies, including forest management in the Canadian Boreal Forest (Scott and Lemieux 2007), plant migration rates under climate change (Malcolm et al. 2002), vegetation responses in China (Zhao et al. 2002), and shifts in the ranges of mammals in the Western Hemisphere (Lawler et al. 2006).

The fundamental assumption underlying how MAPSS treats water balance constraints is that leaf area index (LAI), the surface area of leaf canopy per unit of land surface area, will reach a maximum when all the available soil water is utilized (Neilson 1995). Trees, shrubs, and grasses compete for areal coverage based on their respective rates of transpiration (i.e., soil moisture use) under different potential evapotranspiration conditions. The long-term vegetation type predicted by MAPSS is the one that will maximize the use of the available water, that is, when the vegetation is in equilibrium with the climate (Imbach et al. 2010). Grass area is further limited by the presence of trees because of sunlight competition. The effects of fires are incorporated by removing all shrubs and trees whenever there is sufficient fuel (grass and shrubs) and an ignition trigger (indexed by summer rainfall). Competition between needle and broadleaf forms is determined by the presence of cold winters (where temperatures below the supercooled freezing point of water, $-40^\circ C$, occur at least once in an average year), dry summers (indexed by summer rainfall as a measure of humidity), and the length and warmth of the frost free season.

Cold winters, dry summers, and short, cool frost-free seasons favor conifer forests, while mild winters, wet summers, and long, warm frost-free seasons favor broadleaf forests. Vegetation is further classified into one of six thermal zones—tundra, taiga, boreal, temperate, subtropical, and tropical—based on the mean annual number of frost-free degree days and the mean annual minimum monthly temperature.

Under most conditions in MAPSS, LAI is controlled by water availability. Since LAI is the key mechanism in MAPSS of assessing competition between trees, shrubs, and grasses, the water budget model used in MAPSS has a significant influence on the performance of the model. MAPSS uses a conceptual model to calculate the water budget at the land surface (Fig. 1). Snowmelt is modeled using the degree-day approach, and surface runoff is assumed to be proportional to the degree of saturation.
of the upper soil layer (i.e., all precipitation and snowmelt becomes runoff if the soil is saturated and no runoff is generated if the soil is very dry). The infiltration rate is calculated as the difference between the moisture flux at the surface (precipitation and snowmelt) and surface runoff, instead of the more standard approach of directly calculating the infiltration and applying the residual to surface runoff. Percolation is based on the degree of saturation in the upper soil layer and the available moisture capacity in the lower soil layer. Water percolating through the lowest soil layer is removed as the base flow.

Although the MAPSS water budget model includes most of the processes used in current SVAT schemes, it has some limitations. The process formulations are conceptual and are therefore reliant on calibration. Unlike current SVATs such as the Interaction Soil–Biosphere–Atmosphere (ISBA) of Noilhan and Planton (1989), modified ISBA (MISBA) of Kerkhoven and Gan (2006), and others, the water budget model of MAPSS does not calculate an energy budget. Finally, even though the water budget model operates on the same monthly time step as the vegetation model, the runoff and percolation processes are calculated three times in each monthly time step.

MAPSS has been used to model the equilibrium vegetation distribution of the United States (Neilson 1995), global vegetation distribution under the $2 \times \text{CO}_2$ scenarios from FAR (Neilson and Marks 1994), and global vegetation distribution under the transient scenarios from SAR (Neilson and Drapek 1998). More recently, MAPSS has been combined with the biogeochemical cycling model CENTURY (Parton et al. 1987) to produce a DGVM called MAPSS–CENTURY 1 (MC1) that has been used to simulate the ecosystem dynamics of Alaska under the SAR scenarios (Bachelet et al. 2005). Although MC1 is currently being tested under the Special Report on Emissions Scenarios (SRES) climate scenario results, the MAPSS simulations that are publicly available are those under the FAR and SAR scenarios. Furthermore, preliminary results with TAR scenarios produce vegetation shifts similar to those of the FAR and SAR scenarios in Canada (R. P. Neilson 2007, personal communication). So far, most climate change studies conducted on river basins have not considered the possible effects of vegetation migration on future hydrologic impacts. For example, Kerkhoven and Gan (2011) modeled the effects of climatic change on stream flows in the Athabasca River basin (ARB) and Fraser River basin (FRB) under a variety of SRES climate scenarios from the IPCC’s TAR using MISBA (Kerkhoven and Gan 2006). These simulations all assumed that vegetation distribution in the two basins would not change from the current pattern.

2. Research objectives

What could be the difference between the potential hydrologic impact of climatic change to river basins with and without considering shifts in vegetation patterns induced by climate change? Furthermore, how much the difference will be depends on the vegetation types and climate of the river basins. In this study, the potential hydrologic effects of vegetation shifts (e.g., simulated streamflows) on two river basins (ARB and FRB) of different land uses and climate will be estimated by applying the MAPSS simulated results based on the FAR and SAR GCM scenarios to the MISBA of Kerkhoven and Gan (2006). MISBA was modified from the SVAT-ISRBA of Météo-France and was successfully applied to ARB to model its water and energy fluxes.

The reason behind choosing ARB and FRB, two major river basins of significant economic importance to western Canada, as the study sites is to examine how much climate and vegetation types would make a difference, considering and without considering vegetation shifts, to the potential hydrologic impact of climatic change to two regional-scale river basins located on the leeward and windward sides of the Canadian Rockies, respectively.

3. MISBA scheme

Kerkhoven and Gan (2006) modified MISBA from a SVAT called ISBA, developed by Noilhan and Planton (1989). The original treatment of soil moisture considered the subgrid heterogeneity of the soil moisture capacity by assuming that it followed the Xinanjiang distribution (Zhao 1992). This was modified in MISBA to account for subgrid heterogeneity of soil moisture and rainfall to produce new, highly nonlinear formulations for surface and subsurface runoff. MISBA explicitly models the energy and water processes at the land surface using formulations based on the physics of each process and is therefore both physically and process based. Modeled processes include soil water and heat transfer, solid–liquid storage and phase changes, and vegetative interaction with soil water. MISBA treats subsurface runoff as a nonlinear reservoir, and the land cover is represented as a mosaic of tiles. The meteorological data are adjusted for each tile’s mean elevation to account for a large part of the spatial heterogeneity of land cover and topography. This accounting is primarily limited by the variation in topography within each land cover tile.

MISBA parameters are divided into two categories: four primary parameters that are specified at each grid point (percent sand, percent clay, vegetation type, and
land–water ratio), and 22 secondary parameters, which are determined from the primary parameters, such as depth of soil column, heat capacity of vegetation, and three stomatal resistance parameters. In MISBA, surface albedo, LAI, vegetative cover fraction, and the vegetative roughness length can be treated as either input data or as calibrated parameters. To overcome the challenge of parameter estimation, physical parameters of the ECOCLIMAP land-use dataset (Masson et al. 2003) linked to land surface and soil characteristics were used to define the surface parameters of MISBA. ECOCLIMAP, which covers the entire globe with a horizontal resolution of 30 arc seconds (approximately 1 km), was derived by combining existing land-cover and climate maps, in addition to using the Advanced Very High Resolution Radiometer (AVHRR) satellite data. MISBA is run once for each land cover type present in each meteorological grid square. Next, the runoff generated by each land cover tile in each grid of the flow routing network is aggregated, and the total predicted runoff is routed through a hydrological routing model.

4. Athabasca and Fraser River basins

Located on the leeward side of the Canadian Rocky, the ARB, with a basin area of 133 000 km$^2$, has a continental climate with significant seasonal variation in temperature (Fig. 2). Typical January temperature is about $-20^\circ$C, while that of July is about $17^\circ$C. Typically, June–October are the wet months in ARB, with an average total precipitation of about 300 mm, while winter and spring only experience about 150 mm of precipitation in an average year. ARB is dominated by the boreal forest of relatively small plant and faunal biodiversity, characterized by harsh winters, and water does not limit plant growth. Coniferous forest, mixed wood, and deciduous forest are the dominant vegetation, especially in the upland areas. Willow brush, shrubs, black spruce, and sphagnum moss dominate the lowland areas, which are often poorly drained.

The Fraser River is the principal river of British Columbia (BC). Rising in the Rocky Mountains and flowing northwest through the Rocky Mountain trench to Prince George, the Fraser River then turns south and west to Vancouver, where it flows into the Strait of Georgia 1370 km from its headwaters, draining an area of 230 000 km$^2$. FRB lies between the Pacific Coast of BC and the windward side of the Canadian Rockies, and so it is quite dry, with an average annual precipitation between 300 and 500 mm, similar to that of ARB. The upper reaches of the basin, in the Rocky Mountains, are by far the wettest, averaging 1500 mm of precipitation annually. Average January temperatures vary from $-15^\circ$C in the northern, mountainous regions to $0^\circ$C at the mouth. In June, temperatures range from 20$^\circ$C in the interior to 10$^\circ$C in the high mountains. The FRB is heavily forested, with coniferous forests dominating the western regions, and mixed forests in the eastern regions. There is also significant agriculture along the Fraser River’s main channel.

5. Validation of MISBA in Athabasca and Fraser River basins

The ECOCLIMAP dataset was designed specifically to provide the parameters required by the original ISBA scheme (Masson et al. 2003). Only two of ISBA’s parameters are not included in the dataset: one to describe the subgrid variation of soil water capacity (or soil depth) and one to define the minimum soil moisture capacity at which water could drain from the bottom of the soil column. In the modified MISBA scheme, these two parameters became internally defined and therefore no longer required calibration. Therefore, in MISBA all the parameters were defined a priori, and so no calibration was required (Kerkhoven and Gan 2006). Figure 3 shows that MISBA’s simulated streamflow for the ARB and FRB between 1958 and 2002 agrees well with the observed streamflow ($R^2 \approx 0.60$), which provides the scientific basis of subsequent results simulated by MISBA on the possible hydrologic impact of climate change to the two river basins, with and without the consideration of vegetation shifts. The early significant discrepancy in the FRB before 1964 can be attributed to model start up, particularly the time required to build up snowpacks in the mountains, and systematic biases in the 40-yr
European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) dataset. After 1964, the simulation reproduces the observed annual variations in streamflow for the wet and dry periods ($R^2 = 0.80$, after 1964).

6. Research methodology

A flowchart that summarizes how various datasets used in this study were combined to estimate the effects of potential vegetation shifts on future flows in the study basins is given in Fig. 4. Global MAPSS vegetation data are available at 0.5° resolution, classify vegetation into 63 categories, and provide the dominant vegetation type in each grid square. The ECOCLIMAP land surface dataset used in the climate change simulations of Kerkhoven and Gan (2011) has a 30-arc-second resolution, classifies vegetation into 11 categories, and provides a distribution of vegetation types in each grid square. Before simulations could be conducted with a modified vegetative cover, the MAPSS data had to be reclassified in a manner consistent with the ECOCLIMAP dataset. This was done by combining the 29 MAPSS classes present in the Fraser and Athabasca basins into a total of 11 generalized categories, which were then related to the five dominant ECOCLIMAP classes in the two basins. The ECOCLIMAP classes, permanent snow and C3 cropland, were assumed to be unchanged because the MAPSS resolution was too low to resolve mountain glaciers and the MAPSS methodology was designed to predict potential vegetation patterns.

ECOCLIMAP is a much higher resolution dataset than MAPSS (30 arc seconds versus 0.5°); therefore, areas that are covered by a single MAPSS grid square will contain 3600 ECOCLIMAP grid squares. Because MAPSS identifies a single dominant vegetation class, it is to be expected that the same area in ECOCLIMAP will include smaller areas that are dominated by different vegetation classes.

The current MAPSS and ECOCLIMAP datasets were compared in the ARB and FRB. Both of these basins are dominated by three vegetation classes in the ECOCLIMAP dataset: conifer forest, broadleaf forest, and grassland. Generally, areas that were classified as broadleaf (conifer) forest in MAPSS were predominantly broadleaf (conifer) forest in ECOCLIMAP, although ECOCLIMAP would include smaller fractions of grassland and conifer (broadleaf) forest. Areas that were classified as savannah and shrubland in MAPSS coincided with transition zones between grassland and forested areas in ECOCLIMAP. The taiga/tundra class in MAPSS coincided with the forested areas of the Rocky Mountains, while the tundra class coincided with the unforested/glaciated regions of the Rockies. Table 1 summarizes these identified relationships between the MAPSS and ECOCLIMAP datasets in the ARB and FRB.

For each ERA-40 meteorological grid square of 2.5° resolution, the change in the areal coverage of each vegetation class between the current and future climate distributions predicted by the MAPSS model was calculated. The vegetation distribution of each ECOCLIMAP square was then adjusted by first reducing the coverage of those classes that lost area and then replacing this lost area with vegetation classes that gained area. Vegetation classes that lost area were calculated based on the percent change in areal coverage lost by each class, while vegetative classes that gained area were calculated based on their share of area gained. Therefore, the vegetation shift to ECOCLIMAP data was done at the ERA-40 scale.
Areas classified as taiga and tundra by MAPSS correspond to mountainous areas of the Rockies that are classified as rocks, bare soil, permanent snow, and conifers by ECOCLIMAP, represented in Table 1. These areas are relatively small compared to the Athabasca and Fraser River basins, especially rocks and bare soil (less than 1%), which are not modeled by MAPSS.

For example, assume an ECOCLIMAP square currently consists of 60% conifer trees, 30% broadleaf trees, and 10% grassland and that MAPSS predicted that conifer trees lost 10% of their area while broadleaf trees and grasslands took over one-third and two-thirds of the area lost by other classes, respectively. The future distribution of vegetation for conifer trees equals

$$(60\%)(1 - 0.1) = 54\%,$$

for broadleaf trees equals

$$30\% + (60\% - 54\%)(1/3) = 32\%,$$

and for grasslands equals

$$10\% + (60\% - 54\%)(2/3) = 14\%.$$

MAPSS climate scenarios were based on the predictions of five GCM simulations: the Geophysical Fluid Dynamics Laboratory (GFDL) model, the Goddard Institute for Space Studies (GISS) model, the Oregon State University (OSU) model, and the Hadley Centre with sulfate forcing (HCS) GCM. The GFDL, GISS, OSU, and UKMO GCM simulations were from the FAR and represent equilibrium climates with doubled CO$_2$ concentrations. The HCS model was a transient simulation from the SAR. Because the HCS model was a transient simulation, the MAPSS predictions are based on the GCM results at the end of the HCS simulation, 2070–99, which approximately coincides with a doubling of atmospheric CO$_2$ (Neilson and Drapek 1998).

MAPSS was forced with SAR and FAR outputs of GCMs that assume static land cover. The climate simulated by the GCM is then allowed to equilibrate with this land cover, perturbed by an instantaneous doubling of CO$_2$ or by some transient CO$_2$ concentration profile. The GCM’s future climate outputs therefore include a memory of this static land cover when they are used to force a stand-alone vegetation model, such as MAPSS, to predict a new future land cover. By this approach, we have not considered the feedback effect of vegetation shifts on the climate simulated by the GCMs (Cox et al. 2000), which assumes that the impacts of vegetation shifts are small compared to the impact of sea surface temperature changes to the latent and sensible heat fluxes. Since running a GCM directly coupled with a dynamic vegetation model is beyond the scope of most regional climate change impact studies, this is a necessary assumption.

The climate scenarios used to predict streamflows in the Athabasca and Fraser River basins by Kerkhoven and Gan (2011) were based on SRES simulations from the TAR. To minimize the effect of this inconsistency, only the B2 scenarios for 2070–99 from the TAR were used because this scenario assumes a steady increase in equivalent CO$_2$ concentrations reaching 915 ppmv by 2100 and best approximates the effects of an atmosphere with double equivalent CO$_2$ concentrations relative to 1990 (476 ppmv) (Canadian Centre for Climate Modelling and Analysis 2007).

The B2 of the IPCC’s SRES climate scenarios projects an emphasis on both local and regional solutions to economic, social, and environmental sustainability, with continuously increasing global population, at a rate lower than A2; intermediate levels of economic development; and less rapid and more diverse technological change than in the B1 and A1 storylines. In contrast, the A1 scenarios project a future world of very rapid economic growth, global population that peaks in

### Table 1. Approximate relationships between MAPSS and ECOCLIMAP vegetation classes.

<table>
<thead>
<tr>
<th>MAPSS classification</th>
<th>ECOCLIMAP classification</th>
<th>Bare soil</th>
<th>Rocks</th>
<th>Perm snow</th>
<th>Broadleaf</th>
<th>Conifer</th>
<th>Grassland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>Broadleaf</td>
<td>0.80</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mixed</td>
<td>0.45</td>
<td>0.45</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Conifer</td>
<td>0.10</td>
<td>0.80</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Savanna</td>
<td>Broadleaf</td>
<td>0.45</td>
<td>0.05</td>
<td>0.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mixed</td>
<td>0.25</td>
<td>0.25</td>
<td>0.50</td>
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</tr>
<tr>
<td></td>
<td>Conifer</td>
<td>0.05</td>
<td>0.45</td>
<td>0.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shrubland</td>
<td>0.30</td>
<td>0.30</td>
<td>0.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grassland</td>
<td>0.10</td>
<td>0.10</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taiga/tundra</td>
<td></td>
<td>0.25</td>
<td>0.25</td>
<td>0.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tundra</td>
<td></td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
midcentury and declines thereafter, the rapid introduction of new and more efficient technologies, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1B scenario represents a balance between clean technology, fossil fuel, and nonfossil energy sources.

In general, the SRES B2 scenario assumes steady, moderate increases in greenhouse gases, reaching approximately 12 gigatons of carbon per year (GtC yr\(^{-1}\)) by 2100, relative to the low-emission B1 scenario at approximately 5 GtC yr\(^{-1}\) by 2100 and high-emission A2 and A1FI scenarios at approximately 30 GtC yr\(^{-1}\) by 2100. Total emissions under the B2 scenario are generally less than the A1B scenario, where global emissions peak at approximately 17 GtC yr\(^{-1}\) in midcentury and decline to approximately 14 GtC yr\(^{-1}\) by 2100 (Houghton et al. 2001).

The late time period (2070–99) allows for sufficient time for vegetation shifts to occur. A total of 35 hydrologic simulations (each a combination of five vegetation scenarios and seven GCM climate forcings) were performed on each basin. Since this methodology mixes the results of different GCM simulations (e.g., vegetation from a relatively warm and dry GCM with climate forcings from a relatively cool and wet GCM) the range of final results will tend to be an overestimate of the actual potential range, especially if the process is dominated by negative feedbacks on runoff since this will tend to exaggerate the predictions of inconsistent combinations of GCMs.

The predicted change in mean temperature between 50° and 60°N latitude for the FAR and SAR simulations used by MAPSS were 3.2°C (HCS and OSU), 4.3°C (GISS), 5.0°C (GFDL), and 7.4°C (UKMO) (Neilson and Draper 1998). The seven SRES B2 scenarios ranged from 2.3° to 6.3°C in the Athabasca basin and from 2.6° to 5.0°C in the Fraser basin (Fig. 5a). The B2 scenarios therefore typically predict less severe climate change than most of the other FAR scenarios but more than the SAR scenario, indicating that vegetative shifts under the B2 scenario probably lie somewhere in the middle of the ranges predicted by the five vegetation scenarios.
distributions simulated by MAPSS based on five GCM climate scenarios.

From the above research methodology, we have attempted to address uncertainties associated with potential hydrologic impact of climate change with and without considering shifts in vegetation patterns induced by climate change. We have also addressed uncertainties associated with temperature and precipitation changes by using climate projections of multiple GCMs.

7. Discussion of results

Figure 5a is a plot of changes in temperature and precipitation in the Athabasca and Fraser River basins with respect to the 1960–90 baseline under the B2 SRES scenario by the end of the twenty-first century (2070–99). As expected, the GCMs consistently predict temperature increases in both basins, averaging +3.3°C and +3.2°C in the Athabasca and Fraser River basins, respectively. There is also similar variance in precipitation, with the models generally predicting increases in annual precipitation that average +8% and +7% in Athabasca and Fraser River basins, respectively. However, increased temperatures result in significant decreases in snow water equivalent (SWE) in both basins (Fig. 5c).

Kerkhoven and Gan (2011) showed that these changes translate to significantly different changes in runoff in FRB and ARB. In FRB runoff is generally higher when precipitation is higher (Fig. 5b), but in the Athabasca basin, there are significant declines in runoff, even when precipitation increases significantly. The relationship between runoff and SWE is also different in the two basins. In ARB the simulations generally predict runoff declines that are directly proportional to declines in SWE, except for the anomalous third climate configuration of the Met Office Unified Model (HadCM3) that predicts very large increases in winter precipitation that overcome the effects of a shorter winter snow season, resulting from rising winter temperatures. However, while this increase in the maximum winter snowpack translates into stronger spring runoff, much warmer and slightly drier summers result in a net decline in the annual flow. Although increased temperatures dramatically reduce the size of the winter snowpack in the Fraser basin, some of the GCMs produce significant increases in annual flows, while the other GCMs predict small declines, despite much larger SWE declines than occur in the Athabasca. The Fraser basin, however, is much wetter than the Athabasca, especially in the winter months. As a result, winter and spring rainfall often falls on a saturated surface, unlike in the Athabasca basin, where a much higher proportion of rainfall never reaches the river network system because it falls on relatively dry soils. Again, these results are consistent with the prediction of the other SRES scenarios of Kerkhoven and Gan (2011).

The MAPSS predicts changes in equilibrium vegetative cover in western Canada under the five projected future climates (Fig. 6). All the scenarios predict the encroachment of temperate conifer forest in areas currently dominated by mountain taiga forest and the conversion of conifer forest on the Pacific Coast to mixed forest. Most of the scenarios predict large increases in grassland in the British Columbia interior and a southern and eastern movement of conifer parkland savanna into areas currently dominated by mixed parkland savanna. The scenarios differ in their predictions of the changes in the boreal forest. GISS and HCS predict large increases in mixed forest, while GFDL and OSU predict an expansion of parkland conifer savanna. There are also significant differences at the interface between prairie grasslands and parkland savanna. GFDL, GISS, and UKMO predict relatively small changes in prairie grassland area, while HCS and OSU predict significant expansion of conifer savanna.

These differences can best be explained as a reflection of the sensitivity of vegetation to the precise water balance on the leeward side of the Rocky Mountains, which usually are projected to become warmer and receive more precipitation. Warmer temperatures lead to increased evaporation rates that may or may not offset the effects of increased precipitation. In the wetter models, trees can expand into what is now the dry prairie land. In the boreal forests, the shift will depend largely on the balance between winter and summer warming. Winter warming reduces the number of killer frosts and encourages the expansion of broadleaf forests, while summer warming can increase fires, which encourage the expansion of savanna and grassland.

The effect of these changes on vegetative cover in the two basins is summarized in Fig. 7. In the Athabasca basin, under some scenarios, the areal coverage of broadleaf (GISS and HCS) or conifer (UKMO) forests are projected to increase at the expense of grasslands, while others (GFDL and OSU) project modest increases in grassland area. In the Fraser basin, most of the scenarios project moderate increases in grassland area (GFDL, HCS, and OSU), while GISS projects a significant increase in conifer forest at the expense of grassland and broadleaf forest. Unlike the other scenarios that project conifer forest to maintain its dominance of most of the basin, the warm UKMO scenario projects conifer-forested area to drop to 45% of the basin area because of a dramatic expansion of grasslands in the central Fraser basin, as well as significant increase in broadleaf forest in the northwestern region of the basin.
Each of the five MAPSS vegetation scenarios was used to define the vegetation cover for the seven GCM simulations of the B2 emission scenarios for the 2070–99 time period. For the five vegetation shift scenarios, Fig. 8 summarizes the modeled relationships between changes in basin-wide land cover types and changes in mean annual maximum snowpack and mean annual runoff. Changes in the simulated snowpack and runoff are strongly affected by changes in the basin area covered by grassland; it can be seen that both runoff and snowpack increase steadily as the fraction of the grassland land cover type in both the ARB and FRB increases (Fig. 8a). This is a reflection of the tendency for more snow to accumulate in open grassland areas than forested areas, due primarily to differences in sublimation rates (Pomeroy et al. 1998). Most of the scenarios project relatively modest changes in annual runoff and SWE; however, the UKMO, with its large increase in grassland area in the British Columbia interior, projects a 58% increase in the mean annual snowpack and a 13% increase in the mean annual flow while the GISS and HCS, which project large decreases in grassland area in the upper Athabasca, produce 30%–35% less snow and 7%–8% less annual runoff.

None of the other vegetation types show a similar, consistent strong relationship (Figs. 8b–d). In most of the scenarios there is a strong negative correlation between changes in conifer forest area and runoff and SWE, except in the cases of the GISS and HCS scenarios in the Athabasca basin that predict large increases in broadleaf forest area at the expense of conifer and grassland area. Most of the apparent relationship between changes in conifer-forested area and runoff can be attributed to the fact that, in most cases, changes in grassland area come at the expense or benefit of conifer-forested area.

Another variation on this can be seen in the effect of broadleaf forest area on SWE and runoff (Fig. 8c). In the Fraser basin, increases in broadleaf area correlates with increases in both SWE and runoff, while the opposite is seen in the Athabasca basin. This can be explained by differences in the relationship between grasslands and broadleaf forests in the two basins. In the Athabasca, grassland area tends to decline in scenarios where

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**FIG. 6.** MAPSS equilibrium vegetation types under (a) current conditions, (b) GFDL FAR, (c) GISS FAR, (d) Hadley Centre with sulfate forcing (HadCMS) SAR, (e) OSU FAR, and (f) UKMO FAR (http://www.fs.fed.us/pnw/mdr/mapss/). (g) Current vegetation types according to the ECOCLIMAP dataset.
broadleaf forests expand into the boreal forest, while in the Fraser basin, scenarios that project large increases in grassland area in the British Columbia interior also project increases in broadleaf-forested areas on the leeward side of the Coast Range and Rocky Mountains (e.g., Figs. 6b,f). The relationship between snowpack and runoff changes with changes in rocks and bare soil is particularly weak (Fig. 8d), although much of this is because the projected changes for this land cover type are very small relative (±1%) to the other land cover types (±10%–25%).

There is also a strong linear relationship between changes in the annual maximum SWE and annual runoff, both in terms of percent change (Fig. 9a) and absolute
change (Fig. 9b). Generally, a 4% change in SWE approximately results in a 1% increase in the mean annual runoff, and a 1-mm increase in SWE results in a 1.1-mm increase in the mean annual runoff. These relationships hold true in both basins over a wide range of GCM-projected climate conditions and vegetation responses, suggesting that most changes in the mean annual flow can be mainly attributed to changes in SWE.

Figure 10 compares the estimated basin-wide changes in snowpack and runoff when vegetation shifts are considered with the changes when the shifts are not considered. The distance that individual points lie from the dashed 1:1 line indicate the relative importance of the projected vegetation shifts on runoff and snowpack. Points that lie above the 1:1 line indicate scenarios where the vegetation shift produces an increase in runoff or snowpack relative to the case where vegetation shifts are not considered. The general impact of including the effect of vegetation response to climatic change is to increase runoff in the FRB but decrease runoff in the ARB (Fig. 10a; FRB points all fall above the 1:1 line, while ARB points all fall below the 1:1 line), a reflection of differences in how snowpacks in these basins respond to vegetation shifts (Fig. 10b). However, differences in runoff between the shifted vegetation and historic vegetation scenarios are relatively small, as can be seen from the fact that all the points in Fig. 10a fall very close to the 1:1 line.

The results presented in this study have several limitations because vegetation migration patterns are not limited to the effect of climate change only, as is the case of MAPSS. Human activities, such as logging or agriculture, and forest fires could significantly alter future vegetation patterns. Moreover, the simulations involve the combination of different GCM projections under different emission scenarios and often at different time
scales (i.e., steady-state equilibrium versus transient simulations). If the dominant feedback mechanism were positive (e.g., if warm and dry climate conditions favored vegetation shifts that resulted in less runoff), this would be relatively unimportant because the range of final results would be dominated by consistent combinations of GCMs. However, if the relationship between vegetation shifts and stream flows were negative, the outliers in the final results would be dominated by inconsistent combinations of GCMs, and the estimated range of potential outcomes would be exaggerated.

8. Summary and conclusions

Climate change could lead to drier conditions in the ARB because of increased temperatures, encouraging forest retreat, and grassland expansion. Since open grasslands tend to have deeper snowpacks than forested areas, yielding increased spring runoff and mean annual flow, a negative feedback is produced that can mitigate some of the flow losses that might otherwise occur. This process was most evident in the central FRB, which is considerably drier than the mountainous regions along the basin’s outer boundary. However, under several GCM projections, flow in the Fraser River is expected to increase because of significant increases in rainfall that overcome decreases in the winter snowpack. Vegetation shifts in mountainous regions are expected to be dominated by conifer/broadleaf competition, which were not found to translate into significant changes in annual runoff yield. The shift to grassland will therefore tend to result in even larger increases in runoff in the FRB as a whole.

In the ARB, several scenarios projected an expansion of the boreal forest southward toward areas that are currently a mix of forest and grassland. The resulting loss of grassland area resulted in decreased flows in three of the MAPSS projections (GISS, HCS, and UKMO). All the GCMs project significant increases in annual temperatures in the midlatitudes, and therefore, evapotranspiration should increase. Boreal forest thrives under colder and wetter conditions as compared to grassland. Therefore, in order for boreal forest to outcompete grassland in a warming environment, soil moisture conditions must become significantly wetter. Since these MAPSS projections predict a southward expansion of the boreal forest, this suggests that the water budget model used in MAPSS projects that soils will become wetter in much of ARB. This is inconsistent with the projections of the more detailed, hydrologic modeling employed in MISBA, which projects drier conditions in the ARB.

The projection of MISBA should have more basis than that of the water budget model used in MAPSS given that MISBA is a physics-based SVAT, validated in ARB. In this case, the aforementioned negative feedback mechanism is lost because the two hydrologic models do not communicate with each other. This results in MAPSS projecting vegetation shifts that respond to increased soil moisture, while MISBA projects drier conditions and decreased stream flows. This inconsistency highlights the importance of the consistent treatment of water and energy balances in hydrologic and vegetation models and suggests that the treatment of hydrologic factors in vegetation models needs to be as similar as possible before detailed conclusions can be drawn from a series of stand-alone simulations. Ideally, a detailed hydrologic land surface scheme should be coupled with the vegetation model.

Overall, the changes in runoff volume due to shifts in vegetation are relatively small, even in cases where an unrealistic interaction between different hydrologic models is probably overestimating the likely range of flows (e.g., probably GISS and HCS in the ARB and possibly UKMO in the FRB). Half the scenarios project changes in runoff between $-1\%$ and $+3\%$, and even the

![Fig. 10. Changes in (a) runoff and (b) SWE with a vegetation shift (averaged across the five MAPSS scenarios) and without a vegetation shift (ECOCLIMAP current conditions).](image-url)
most extreme combinations project changes within $\pm 15\%$, despite the tendency of the employed methodology to overestimate the potential range of changes.

These results, however, cannot account for the response of humans to climatic change or potential impacts of insect infestations because these processes are not modeled by MAPSS. While declining forested area will tend to mitigate streamflow declines, much of this decline would be due to increased forest fires, which are often actively suppressed by government agencies. The vegetation models also cannot account for changes in agricultural practices, as farmers change their crops in response to climatic change. In addition, the expansion of new insect species such as the mountain pine beetle, which has already devastated the FRB and could potentially cross the Rocky Mountains into the ARB (Carroll et al. 2006), could cause more changes to the land cover of both basins than the more direct climate-induced impacts on vegetation modeled by MAPSS. Finally, the vegetation models used in this assumed equilibrium condition may take more than a century to occur, and in some cases the equilibrium condition may never occur if species migration rates are too slow and key ecological functions are lost and never replaced.

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