

Impacts of Climate Change on Wintertime Precipitation, Snowmelt Regime, Surface Runoff and Infiltration in the Northeastern USA during the 21st Century

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ABSTRACT

Climate model simulations of 21st century winter climate under low and high greenhouse gas emission scenarios were used to assess the influence of climate change on precipitation, snowmelt regime, surface runoff and infiltration in the northeastern USA. Temperature and precipitation projections were statistically downscaled and used as inputs to the Variable Infiltration Capacity (VIC) hydrological model to simulate snow melt, surface runoff, infiltration, soil moisture, and subsurface runoff. Previously published estimates from the climate model simulations showed that the lower emission scenario resulted in substantially lower annual average surface air temperature warming (+2.9 °C) compared with the high emission scenario (+5.3 °C) for 2070-2099 compared with 1961-1990. Model simulations also projected increases in winter and, to a lesser extent, spring and fall precipitation, but no changes in summer precipitation for 2070-2099. Model projections indicated decreases in total snowfall during the 21st century. Increasing winter precipitation, earlier snowmelt, and a shift from snow to rain resulted in increases in surface runoff, infiltration, and subsurface flow during the winter. VIC model simulations are consistent with a shift in the timing and overall amount of infiltration resulting in greater infiltration and subsurface flow in winter. These hydrologic changes would result in increasing winter stream flows and decreasing spring stream flows. Groundwater recharge would shift progressively from spring into winter months. An earlier recession in groundwater levels in the spring and summer could also be expected during the 21st century. Under the current hydrologic regime, a substantial amount of water remains in storage in the snowpack through the end of winter (March 21st). By the end of the 21st century, particularly under the higher emission scenario, that supply of water has largely melted and infiltrated by March 21st.

Keywords: climate change, hydrologic responses, infiltration, groundwater recharge, VIC model

INTRODUCTION

One of the most important aspects of climate change is how it could affect hydrologic and cryospheric regimes in ways that could have adverse consequences for water resource management (Alder, 2007). For the northeastern United States (NE USA) observations and climate modeling indicate an ongoing and projected future warming and increase in precipitation (Hayhoe et al., 2007). Future increases in precipitation are projected to be confined to winter, and, to a lesser extent, spring and fall months. Historical trends in a variety of hydrologic and

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cryospheric variables are consistent with expected responses to observed surface air temperature warming. Regional climate modeling and hydrologic modeling suggest that observed trends are likely to continue and new trends, such as decreases in soil moisture and summer low flows owing to increases in evapotranspiration, are likely to emerge (Hayhoe et al., 2007). One dimension of hydrologic response to climate change that has received little attention in the NE USA is the potential impact on infiltration and groundwater recharge. Changes in winter precipitation (amount, intensity, and proportion as snow), snowmelt regime, soil temperature regime and rate of evapotranspiration could affect the timing and amount of groundwater recharge. Groundwater recharge is important for maintaining water supplies in aquifers, maintenance of stream flows under low flow conditions, and maintenance of cold water refugia.

Recent reports using observational data from the U.S. Historical Climatology Network (Williams et al. 2005) have shown that the NE USA warmed by about 0.8 °C during the 20th century and that warming has been greatest in winter and accelerated since 1970 (Keim et al., 2003; Trombulak and Wolfson, 2004; Hayhoe et al., 2007). Analyses have also shown that the region has gotten wetter, by about 10 cm of additional liquid precipitation during the 20th century (0.1 cm per yr), although this trend appears to have reversed during the period 1970 through 2000 (Keim et al., 2005; Hayhoe et al., 2007). Trends in hydrologic response variables include earlier lake ice-out (Hodgkins et al., 2002), river ice-out (Hodgkins et al., 2005), and snowmelt runoff (Hodgkins et al., 2003). Trends also include decreasing thickness of river ice (Huntington, 2003), decreasing ratio of snow to total precipitation (Huntington et al., 2004), decreasing snowfall (Hamilton et al., 2003; Huntington et al., 2004, Hayhoe et al., 2007), decreases in snow cover days (Hayhoe et al., 2007), increasing density of late-winter snowpack (Hodgkins and Dudley, 2006), and increasing stream water temperatures (Huntington et al., 2003; Juanes et al., 2004).

The hydrologic responses noted above could influence both the timing and amount of surface runoff, soil moisture, albedo, infiltration, and subsurface flow during the winter period with potential consequences on water resources and flood occurrence. Here we use climate and hydrologic projections developed for a regional assessment (Hayhoe et al., 2007) to further investigate projected changes in these variables during the winter. Our objective was to evaluate how projected 21st century winter precipitation and snowmelt are partitioned between runoff and infiltration and, once water had infiltrated the soil, how soil water is partitioned between evapotranspiration, change in soil moisture and subsurface flow.

METHODOLOGY

This study was based on the climate and hydrologic projections conducted for a regional assessment using two coupled atmosphere-ocean general circulation models (AOGCMs) that were “forced” with two emission scenarios for the 21st century (Hayhoe et al., 2007). This study focused on the wintertime period only, here defined as December 21st through March 21st. The resulting climate projections were used as inputs for the Variable Infiltration Capacity (VIC) hydrologic model to generate a range of potential future hydrologic conditions. The data sources, emission scenarios, and climate and hydrologic model descriptions are detailed in Hayhoe et al. (2007). The two emission scenarios selected for analysis were the B1 (low emissions) and the A1FI (fossil fuel intensive-high emissions) defined by the IPCC Special Report on Emission Scenarios (SRES, Nakicenovic et al., 2000). The two AOGCMs were the HadCM3 (Pope et al., 2000) and the PCM (Washington et al., 2000). These models were selected because they have been shown to be among the best in a comparison of nine models for this region (Hayhoe, written communication). For the hydrological modeling, monthly AOGCM temperature and precipitation fields were statistically downscaled to daily values with a spatial resolution of 1/8 degree, after Wood et al. (2002), as described by Hayhoe et al. (2007).

Downscaled temperature and precipitation were then used as input to the VIC model. Other required meteorological data, such as radiation, pressure and humidity are generated by the VIC model using statistical relationships with the temperature and precipitation data. The VIC model simulates the full water and energy balance at the earth’s surface by modeling processes such as

canopy interception, evapotranspiration, runoff generation, infiltration, soil water drainage, and snow pack accumulation and melt (Figure 1). Model inputs (precipitation, temperature, radiation, etc.), soil properties (porosity, saturated hydraulic conductivity, etc.) and vegetation parameters (leaf area index, stomatal and architectural resistances, etc.) are specified at each grid cell. Model outputs include gridded fields of evapotranspiration, runoff, snow water equivalent (SWE) and soil moisture profiles. The runoff fields (surface and baseflow) from these simulations are then routed through stream networks using a lumped routing model (Hayhoe et al., 2007). This analysis uses projected surface air temperature to partition precipitation as snow or rain. We recognize that the quality of precipitation is determined in a much more complex process where a key variable is air temperature at the point in the atmosphere where water vapor condenses.

Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model

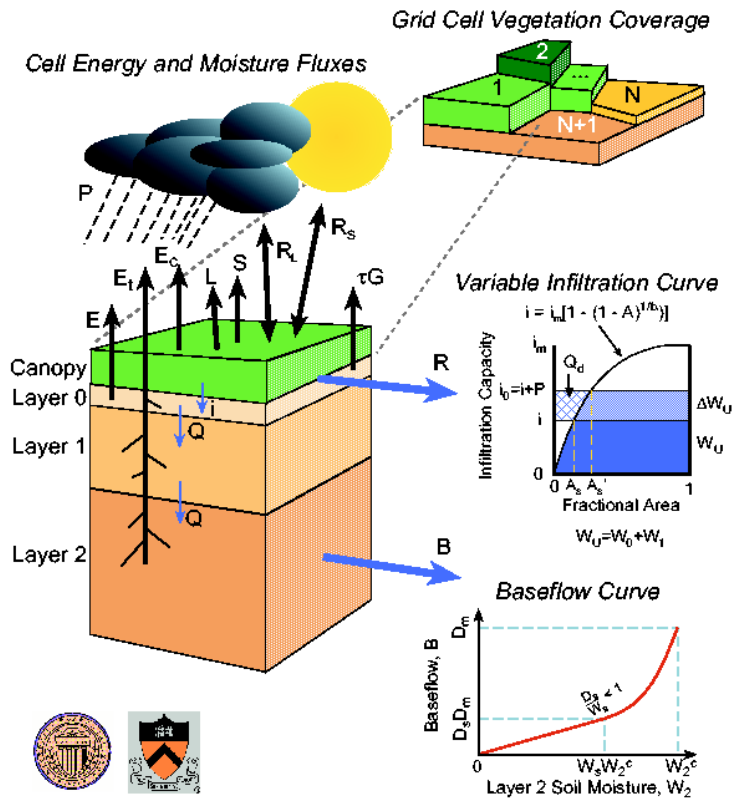


Figure 1. Schematic showing basic processes that are modeled in the Variable Infiltration Capacity (VIC) hydrologic model. Citations for VIC model description can be found in Hayhoe et al.(2007).

It is assumed that the relationship between (although not the actual values of) monthly temperature and precipitation and the sub-monthly forcing statistics such as rain day frequency, ratio of snow/rain, and number of freezing days remains unchanged in the future. This does allow sub-monthly statistics to shift with the mean of the distribution, however, the assumption of no change in the shape of the distribution, particularly in the tails where extreme events occur, is likely to be conservative based on both historical observations (Huntington et al. 2004) as well as future projections (K. Hayhoe et al., personal communication). Potential changes in climate forcings such as diurnal temperature range (DTR), radiation, and cloud cover, as well as external forcings such as vegetation (including the lengthening of the growing season) and land use, are not accounted for in these simulations. This means that the explicit influence of climate change on DTR, temperature or precipitation variance, transpiration fluxes from the extended growing season, and other daily climatological metrics will not be represented by VIC outputs. As stated by

Hayhoe et al. (2007), “*In this sense, the VIC downscaled climate projections are a direct representation of inter-monthly AOGCM forcing, coupled with terrain-related adjustments based on the Parameter-elevation Regressions on Independent Slopes Model (PRISM, Daly et al. 1997) to resolve finer-scale topographical features*”.

In the VIC model, as the fractional wetted grid cell area increases, progressively more precipitation is routed to infiltration, and as the soil moisture content increases more infiltrated water is routed to subsurface flow. The model simulated subsurface flow is not explicitly partitioned into subsurface flow that is routed to streams in the short term (i.e. days following precipitation or snowmelt), versus the component that is routed to streams in the longer term (weeks to months) that contributes to seasonal groundwater storage and release. For the purpose of this study we assume that some fraction of infiltration during the winter is routed through aquifers that are slowly discharged to streams during later spring and summer when there is usually little infiltration.

RESULTS AND DISCUSSION

Climate projections for the northeastern U.S. consistently indicated a high likelihood for increasing winter precipitation for mid and late 21st century compared with the historical period for the northeastern US region (Hayhoe et al., 2007). Winter is defined here as 21st December to 21st March. On average AOGCM projections indicate winter precipitation increasing by 11% for the B1 (lower emission scenario) and 30% for the A1FI (higher emission scenario). These results are consistent with the IPCC AR4 modeling results for this region for December through February for the period 2080 through 2099 for the multi-model ensemble average for the A1B scenario (a substantially lower, i.e. cooler, emission scenario than A1FI) (Meehl et al., 2007) that indicate a 15 to 20% increase in precipitation (Christensen et al., 2007). For the two models considered here the HadCM3 model projects larger increases in winter precipitation than the PCM model for mid and late-21st century for both emission scenarios. Increases are expected on the order of 1 to 2 mm/day for the HadCM3 and 0.5 to 1 mm/day for the PCM model and the increases are expected to be fairly uniform across the spatial domain. Recent projections also suggest that precipitation intensity will also increase (Tebaldi et al., 2006, Christensen et al., 2007).

The ratio of snow to total precipitation is expected to decrease markedly across the region with the largest changes at mid 21st century in the southern and coastal areas. These trends would continue those observed for the latter half of the 20th century in New England states (Huntington et al., 2004) and also observed in the northwestern US (Knowles et al., 2006). Decreases in this ratio progress rapidly during the latter half of the 21st century encompassing the entire region. Absolute decreases in snow to total precipitation ratio are greatest under the HadCM3 A1FI and for the southern and coastal areas where this ratio could decrease by a factor of 2 or more.

The average wintertime snow water equivalent (SWE) declines markedly across the region by mid 21st century and continues to decline progressively into the late 21st century in all model-by-scenario combinations. Declines are greatest in the warmest scenario (A1FI) for the HadCM3 model followed by PCM A1FI, HadCM3 B1, and PCM B1. Mountainous and northern Maine regions that historically averaged 100 to 180 mm SWE for the winter period would decrease to less than 60 mm under the HadCM3 A1FI projection and < 120 mm for all but the highest peaks under the PCM B1.

The decrease in snow cover implied by the substantial decreases in SWE result in a substantial decrease in albedo across the entire region with the largest changes by mid 21st century expected in southern and coastal areas and in the northern and mountainous regions in the late 21st century. The order of declines among model-by-emission projections follows that observed for SWE although the differences among these projections are greater for albedo than SWE. Mountainous and northern Maine regions that historically averaged 0.7 to 0.9 albedo for the winter period would decrease to 0.5 to 0.7 under the HadCM3 A1FI projection and 0.6 to 0.8 under the PCM B1.

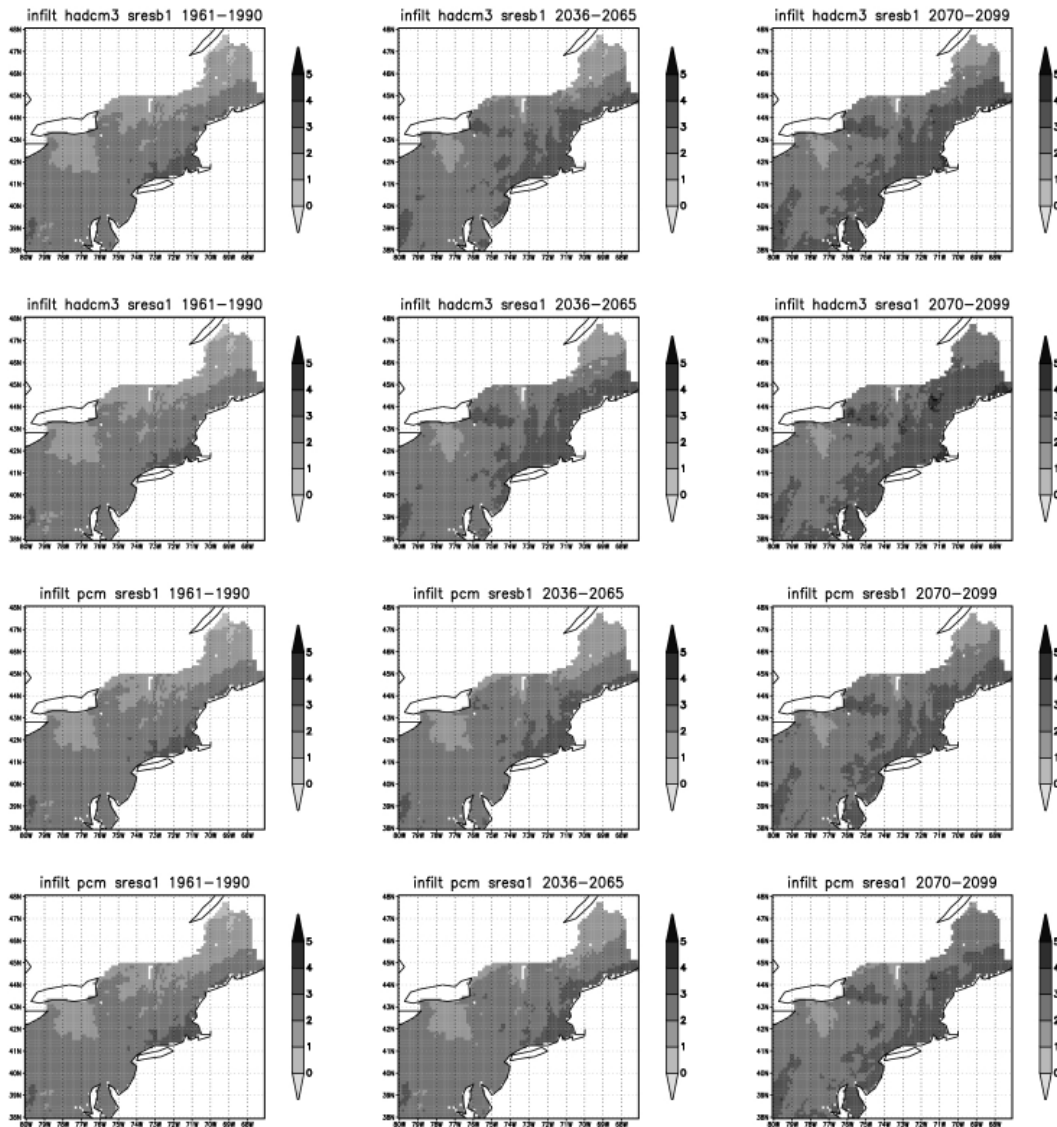


Figure 2. VIC model-simulated historical (1961-1990) and future projected (2036-2065 and 2070-2099) infiltration (mm/day) under the HadCM3 (top panels) and PCM (bottom panels) climate models using SRES B1 (sresb1) and A1FI (sresa1) and emission scenarios.

Surface runoff increases across the region by mid 21st century and continues to increase into the late 21st century in all model-by-scenario combinations. This increase is a result of increasing precipitation, decreasing ratio of snow to total precipitation, increasing snowmelt, and increased soil moisture. The increase in surface runoff is not uniform across the region. In certain areas like the Adirondack Mountains in New York and mountainous areas in Vermont and New Hampshire the increase (0.25 to 0.45 mm/day) is comparatively greater than the projected increases in western New York and north- and south-central Pennsylvania (0.05 to 0.15 or 0.1 to 0.2 mm/day) for the HadCM3 A1FI. The regions having the largest increases in surface runoff have the highest historical average daily winter precipitation levels in the northeastern US and the regions with the smallest increases have the lowest historical average daily winter precipitation.

Infiltration is estimated as precipitation minus surface runoff minus the net change in SWE for the entire winter period and may include contributions from snowmelt. Infiltration during the winter period increases across the region by mid 21st century and continues to increase into the late 21st century in all model-by-scenario combinations (Figure 2). The increases are greatest in

the warmest scenario (A1FI) for the HadCM3 model followed by HadCM3 B1, PCM A1FI, and PCM B1. It is interesting that the increases are greater under the HadCM3 B1 than PCM A1FI suggesting that this variable is somewhat more model dependent than scenario dependent unlike most variables. The increase in infiltration from the historical period to the late 21st century from the HadCM3 A1FI case varies from about 0.5 mm/day in the near coastal regions and in the southwestern quadrant of the domain to 1.5 to 2 or more mm/day further inland throughout the remainder of the area. The biggest increases are in areas experiencing the largest absolute changes in SWE. The smallest changes overall are in the area of western New York and north- and south-central Pennsylvania that have the smallest increases in surface runoff. These are areas that also have both lower than average wintertime precipitation and SWE in the historical and future periods.

Soil moisture increases across most of the region by mid 21st century and continues to increase into the late 21st century in all model-by-scenario combinations. In the southwestern quadrant of the domain the increases are very small, particularly with the PCM projections. The soil moisture data suggest that on average, for the winter, the soils are less than fully saturated therefore it is consistent that infiltration can increase.

Subsurface flow increases across the region by mid 21st century and continues to increase into the late 21st century in all model-by-scenario combinations (Figure 3). The spatial pattern in the increases is similar to that of surface runoff. The increases are greatest in the warmest scenario (A1FI) for the HadCM3 model followed by HadCM3 B1, PCM A1FI, and PCM B1. The increases are greater under the HadCM3 B1 than PCM A1FI suggesting that this variable is somewhat more model dependent than scenario dependent unlike most variables. Subsurface flow increases from about 2 to 3 mm/day in northern coastal regions. In the Adirondack Mountains and the area immediately to the southwest of that area in New York and in the Green Mountains of Vermont the increases in subsurface flow are particularly large from approximately 1.3 – 1.6 to 2.7 -3.0 mm/day.

SUMMARY

Historical (1961-1990) and projected future (2036-2065 and 2070-2099) VIC model simulated water fluxes and snow storage averages for the winter period for the HadCM3 (A1FI) and PCM (B1) climate models (emission scenarios) are shown in Table 1. These model-by-emission scenario combinations span the range of temperature and hydrologic responses that were studied in the regional analysis (Hayhoe et al., 2007). The range of responses illustrates differences between models and differences in possible outcomes that could occur under different emission scenarios. Increases in precipitation, a shift from snow to rain, and earlier snowmelt all result in increases in surface runoff, infiltration, and subsurface flow during the winter that become progressively larger during the 21st century. VIC model simulations are consistent with a shift in the timing and overall amount of infiltration resulting in greater, surface runoff, infiltration, and subsurface flow in winter. These hydrologic changes would result in increasing winter stream flows and decreasing spring stream flows. Groundwater recharge would shift progressively from spring into winter months. Earlier infiltration would result in an earlier recession in groundwater levels in the spring and summer, and potentially lower groundwater levels in late summer and fall as the growing season lengthens and evapotranspiration increases (Hayhoe et al. 2007, Huntington, 2006). Under the current hydrologic regime, a substantial amount of water remains in storage in the snowpack through the end of winter (March 21st). However, by the end of the 21st century, particularly under the higher emission scenario, that supply of water has largely melted and infiltrated by the end of winter.

Table 1. Historical (1961-1990) and projected future (2036-2065 and 2070-2099) VIC model simulated regional average water fluxes and snow storage for the winter period for the HadCM3 climate model and the A1FI emission scenario and the PCM climate model and the B1 emission scenario.

Period	Winter Precip. mm/day	Surface Runoff mm/day	Subsurface Runoff mm/day	Infiltration mm/day	Average Snow Water Equivalent mm
HadCM3 A1FI					
1961-1990	2.54	0.19	1.39	2.22	33.7
2036-2065	2.97	0.25	1.86	2.70	16.1
2070-2099	3.28	0.29	2.15	3.01	4.66
PCM B1					
1961-1990	2.60	0.19	1.34	2.25	34.4
2036-2065	2.70	0.22	1.52	2.43	25.4
2070-2099	3.00	0.28	1.82	2.76	20.9

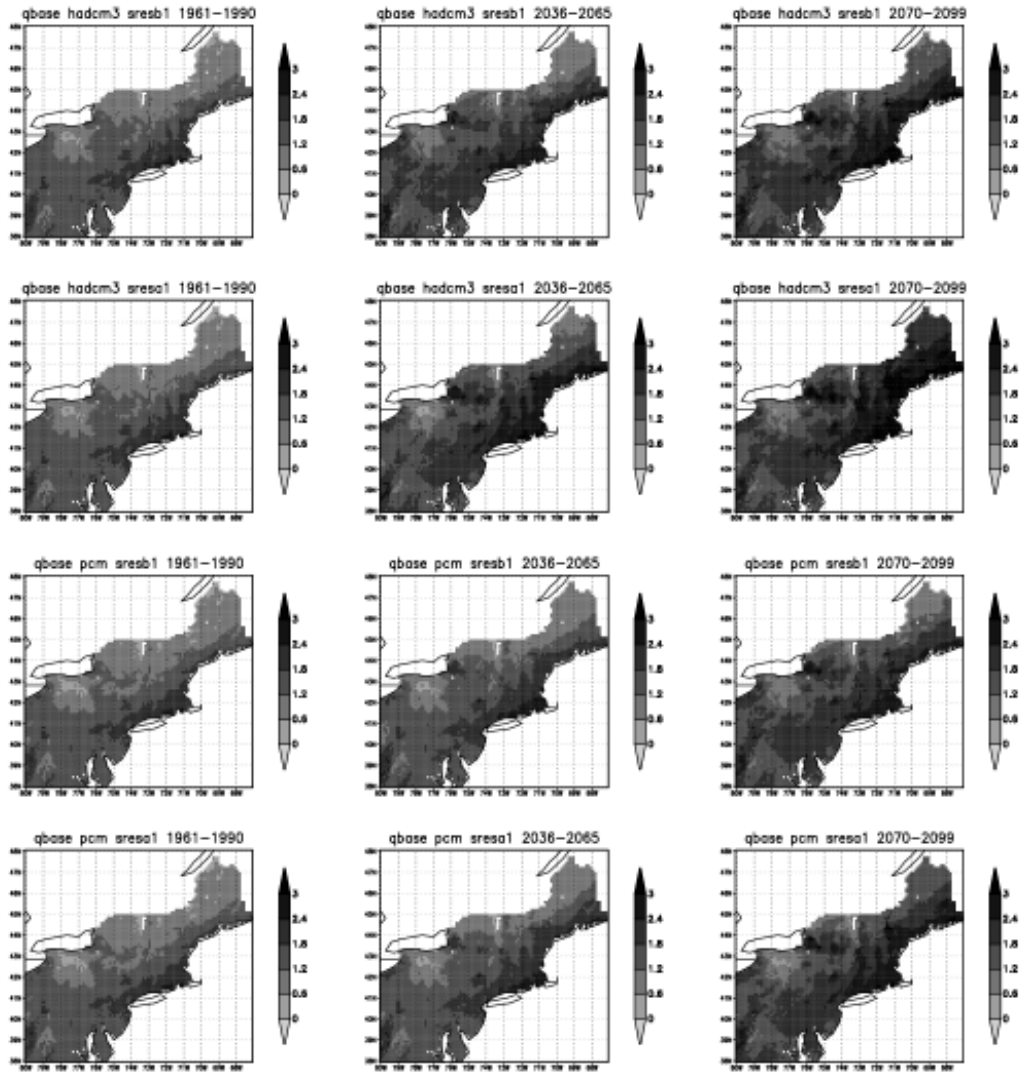


Figure 3. VIC model-simulated historical (1961-1990) and future projected (2036-2065 and 2070-2099) subsurface flow (mm/day) under the HadCM3 (top panels) and PCM (bottom panels) climate models using SRES B1 (sresb1) and A1FI (sresa1) and emission scenarios..

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