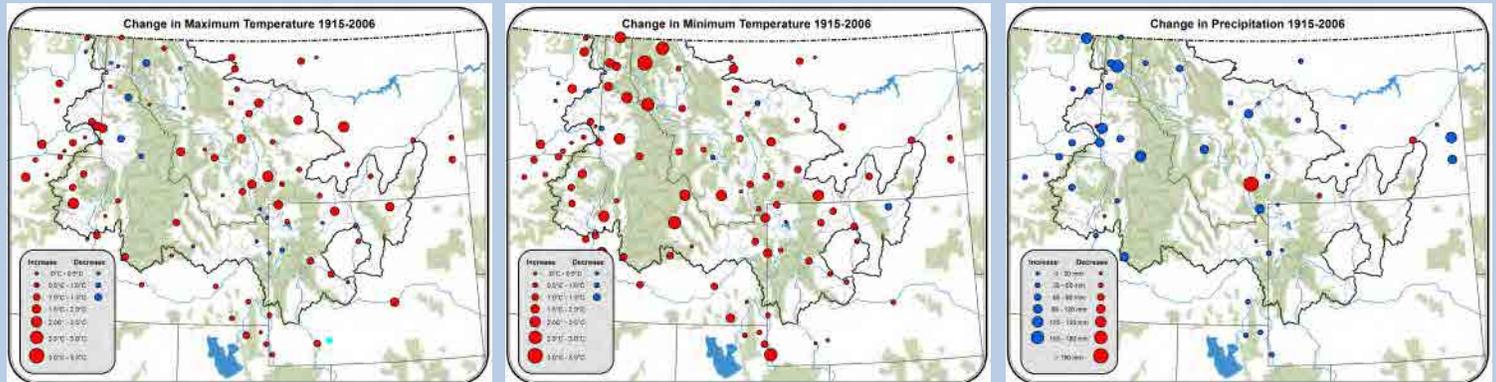


## Observed trends in Northern Rockies temperature and precipitation

Temperature increased  $\sim 1.2^{\circ}\text{F}$  ( $0.7^{\circ}\text{C}$ ) for maximum temperature and  $\sim 2.1^{\circ}\text{F}$  ( $1.2^{\circ}\text{C}$ ) for minimum temperature averaged for Northern Rockies stations, 1916–2006<sup>1</sup>. This is comparable to the U.S. national average\* of  $1.1^{\circ}\text{F}$  ( $0.6^{\circ}\text{C}$ ) for the same period<sup>2</sup>. 77% of stations had increasing maximum temperature, and 94% of stations had increasing minimum temperature. The change in annual precipitation, averaged over the region, is an increase of  $+9.0\%$  since 1916<sup>1</sup>, slightly more than the U.S. national average of about  $8.1\%$ <sup>2</sup>. Precipitation increased at 81% of stations, and the increase was primarily in spring, summer, and fall.



GYA trends in maximum temperature (left), minimum temperature (center) and precipitation (right), 1916-2006.

\*Maps: R. Norheim. Data: NOAA NCDC, from USHCN v.2

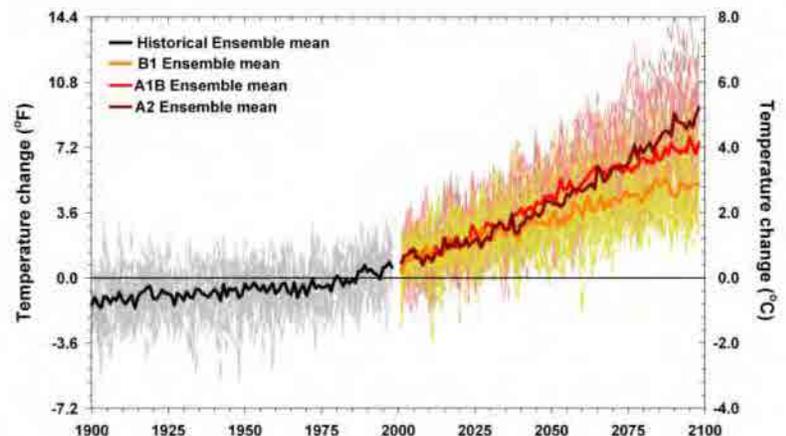
## Projected 21<sup>st</sup> century Northern Rockies climate changes

All global climate models (GCMs<sup>3</sup>) project surface temperature warming in the Northern Rockies in all seasons regardless of uncertainties in modeling or greenhouse gas emissions<sup>4</sup>. These projected temperature increases exceed observed 20th century year-to-year variability, generally by the 2040s. Many climate models project increases in precipitation during the winter and decreases in summer, however, projected precipitation changes are comparable to 20<sup>th</sup> century variability. Beyond mid-century, climate change projections are less certain because they depend increasingly on greenhouse gas emission rates in the next few decades.

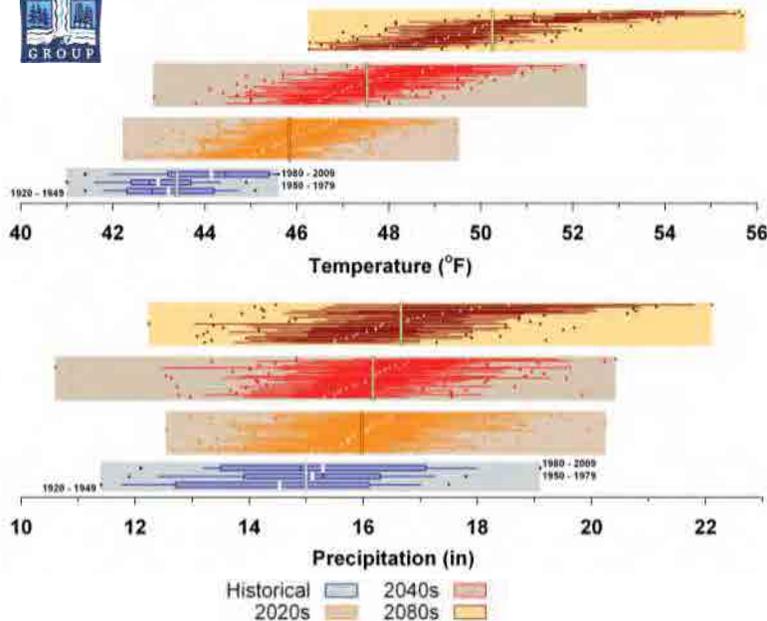
**Table 1. Expected Northern Rockies regional climate changes**

	Temperature change ( $^{\circ}\text{F}$ )		Precipitation change (%)	
	B1 (low)	A1B (med.)	B1 (low)	A1B (med.)
<b>2020s</b>	+2.1 (+1.2 to +3.9)	+2.3 (+1.3 to +3.3)	+3 (-27 to +29)	+3 (-14 to +25)
<b>2040s</b>	+3.0 (+1.5 to +5.5)	+3.9 (+2.5 to +5.9)	+1 (-18 to +20)	+7 (-2 to +34)
<b>2080s</b>	+4.8 (+3.2 to +7.9)	+6.7 (+3.8 to +10.4)	+8 (-8 to +27)	+10 (-12 to +36)

Changes in temperature and precipitation are relative to 1970 -1999, averaged over 117W-105W and 42N-49N. 2020s = 2010- 2039; 2040s = 2030 - 2059; 2080s = 2070 - 2099. B1 is a low greenhouse gas emissions scenario; A1B is higher until about the 2040s, then is moderate (see right). Data: CMIP3 (IPCC AR4 GCMs)<sup>3</sup>



**Figure 1. Northern Rockies and 2001-2099 (color). Heavy lines are ensemble (multiple climate model) averages for B1, A1B, and A2 emissions scenarios.**

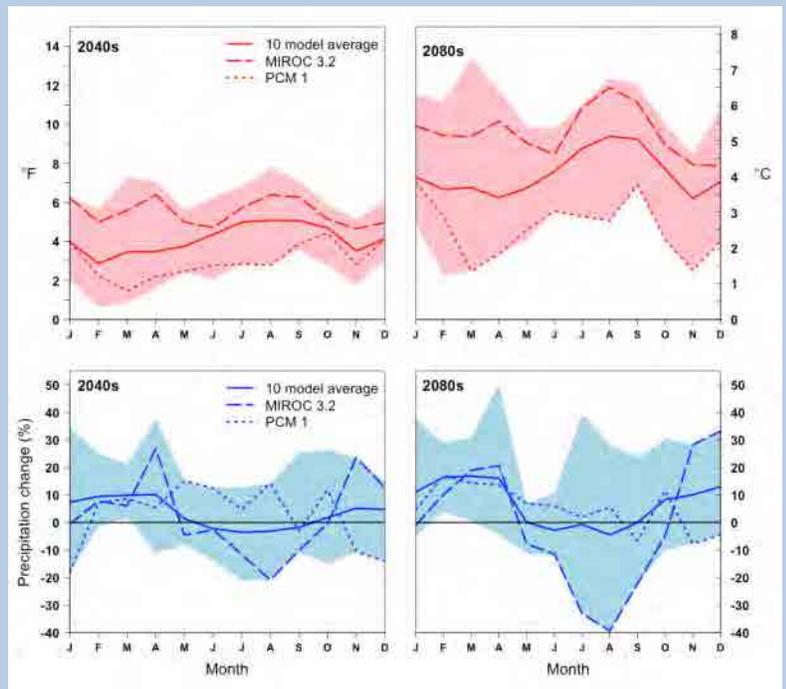
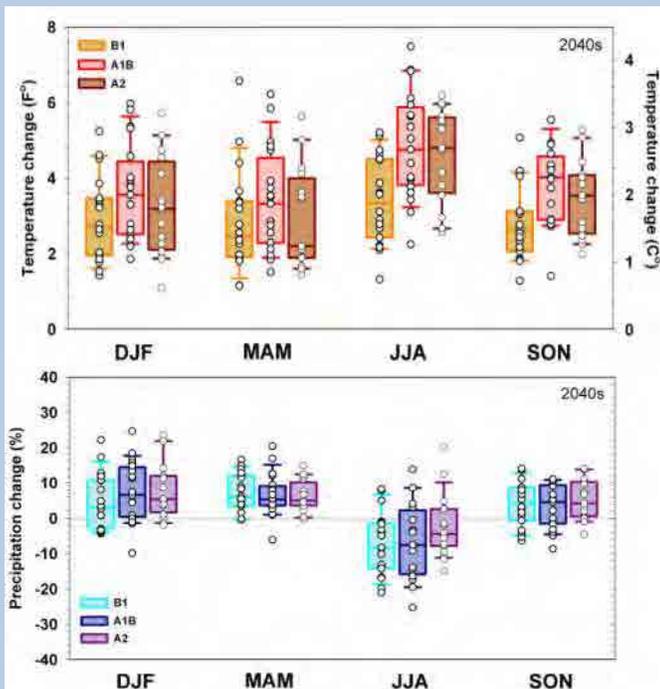


Different climate models project different rates of change in temperature and precipitation because they operate at different scales, have different climate sensitivities, and incorporate feedbacks differently. Comparing the observed climate of the past with projected changes across many climate models (left) for temperature and precipitation provides context for the expected changes. For the 2040s, the lowest modeled mean annual temperature is outside the range of observed temperatures. For precipitation, the future variability is comparable to the historical

Left: Climate ranges for the historical period (HCN) compared to modeled future ranges from GCMs. Range of boxes is low model 5<sup>th</sup> percentile to high model 95<sup>th</sup> percentile. Large vertical bars are A1B ensemble means. Each GCM is represented by a horizontal line (5<sup>th</sup> to 95<sup>th</sup> percentile, white bar is the mean).

## Seasonal climate change in the Northern Rockies

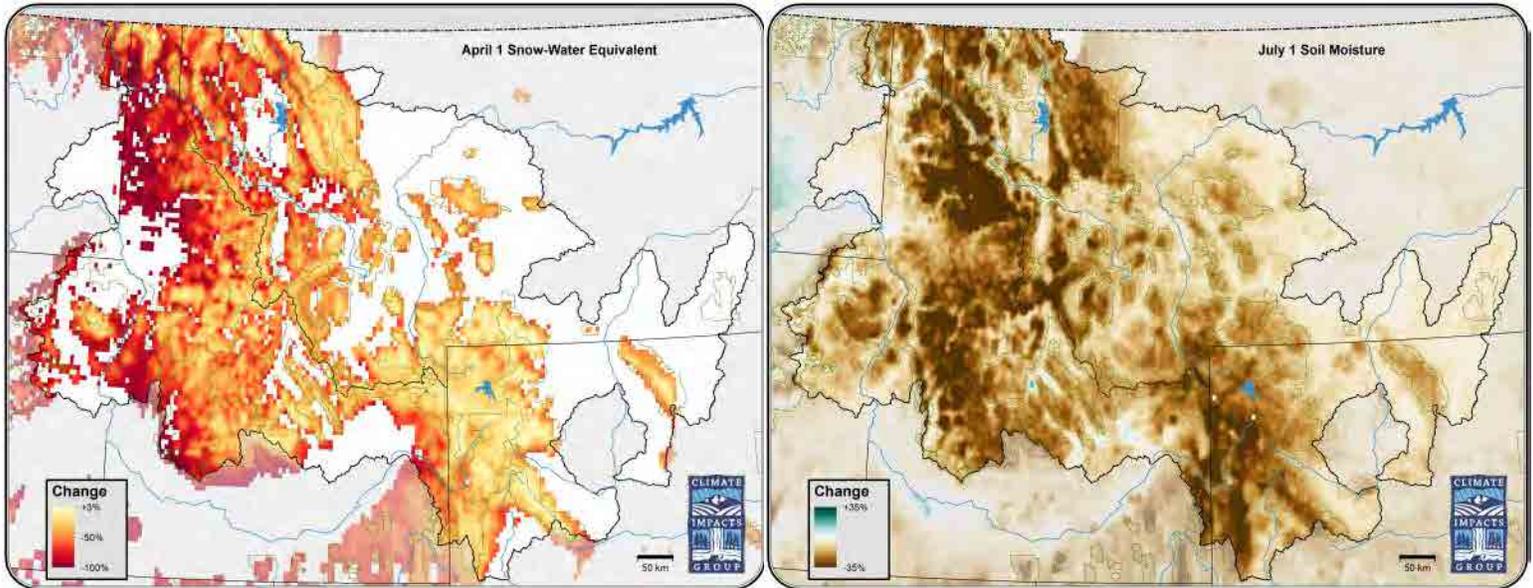
All climate scenarios project warming in all seasons for the region. By the 2040s, climate models project temperature increases of around 3.2°F (1.8°C) for winter, spring, and fall but 4.3°F (2.4°C) in summer. On average, models project increases in precipitation in winter (+8%), spring (+7%), and autumn (+3%) but decreases in the summer (-7%). These changes are averaged across B1 (18 GCMs), A1B (19GCMs), and A2 (15 GCMs) emissions scenarios and compared to 1970-1999 averages.



Left: Projected seasonal climate changes for the Northern Rockies for the 2040s by emissions scenario (B1, A1B, A2) relative to 1970-1999. Each dot is a single climate model projection. Boxes show median (bar inside box), whiskers show 5<sup>th</sup> and 95<sup>th</sup> percentile changes.

Right: Scarce resources sometimes require narrowing to a few representative scenarios when planning for climate change. In this example (right), ten climate models were compared during the historical period to determine which best captured historical climate patterns. The graphs (right) show projected changes in monthly northern Rockies climate for the 2040s relative to 1970-1999. The shaded areas indicate the range of changes expected from 10 climate models that perform best historically. The lines show changes for three climate change scenarios: (1) more warming, drier (Miroc 3.2); (2) less warming, wetter (PCM1); and (3) ten-model average

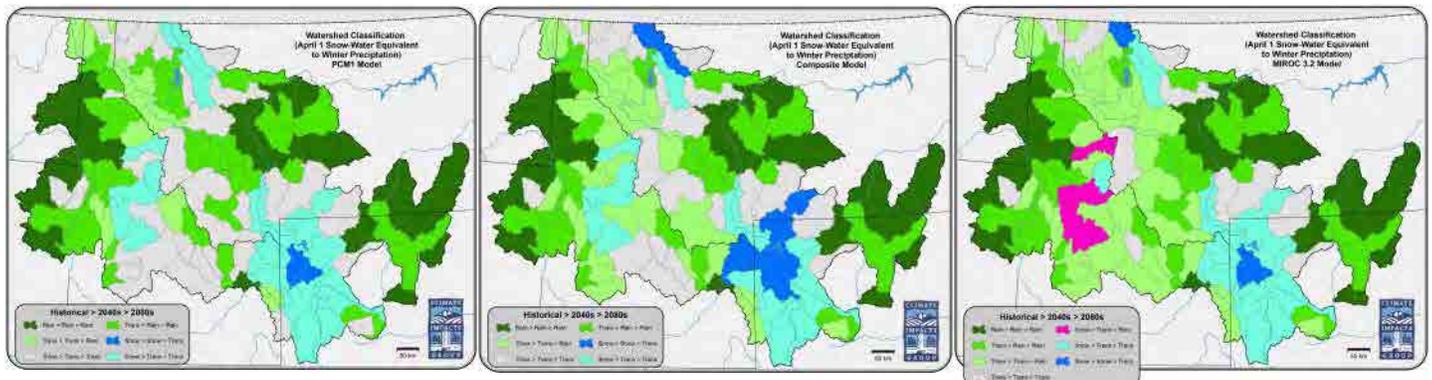
# Projected 21<sup>st</sup> century changes in Northern Rockies hydrology



Projected changes in 2040s April 1<sup>st</sup> snow water equivalent (left) and July 1<sup>st</sup> soil moisture (right) for the GYA (10 climate model average, A1B emissions, relative to 1916-2006). Due to warming temperatures, a higher proportion of precipitation falls as rain during the cool season (Oct. – Mar.) and spring snowpack begins to melt earlier. Snowpack declines are largest at lower elevations. Warmer temperatures cause earlier snowmelt and higher summer evapotranspiration, leading to declines in summer soil moisture.

Hydrologic models use future temperature and precipitation along with local information on soils, vegetation, and other conditions to simulate the hydrologic outcomes of climate change. In the Northern Rockies, snowpack is important in governing streamflow, soil moisture, and habitat for snow-dependent wildlife such as lynx and wolverine. Lower streamflow in late summer also affects habitat quality for resident and migratory fish. Declining snowpack and soil moisture therefore are likely to affect the region by affecting water availability, plant growth, forest health, fire risk, and wildlife habitat.

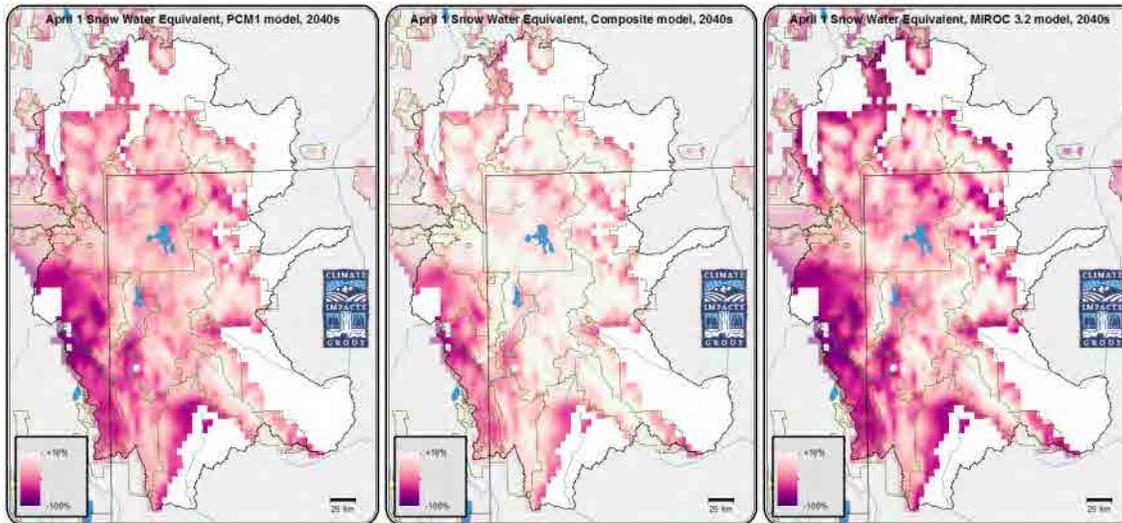
In watersheds where winter precipitation is currently dominated by rain instead of snow, changes in snowpack will not be as profound as “transitional” watersheds where more cool season precipitation currently accumulates as snow. In the highest watersheds, where most cool season precipitation currently falls as snow, temperatures are historically cold enough that watershed hydrology will be less affected by warming until later in the 21<sup>st</sup> century. Below are maps of watershed snowpack vulnerability, defined as “rain dominant” (<10% current cool season precipitation in April 1 snowpack), “transitional” (10% to 40%), and “snow dominant” (>40%). Most transitional watersheds become rain dominant, and all snow dominant watersheds become transient by the 2080s under all three scenarios.



Projected changes in the ratio of April 1<sup>st</sup> snowpack to total cool season precipitation (Oct. – Mar.) for the 2040s and 2080s in the Northern Rockies for a less warm, wet climate model (left), the average of 10 climate models (center), and a relatively warm climate model (right). Some watersheds remain transitional, but most historically transitional watersheds become rain dominant and most historically snow dominant watersheds become transitional.

## Projected 21<sup>st</sup> century changes in GYA hydrology

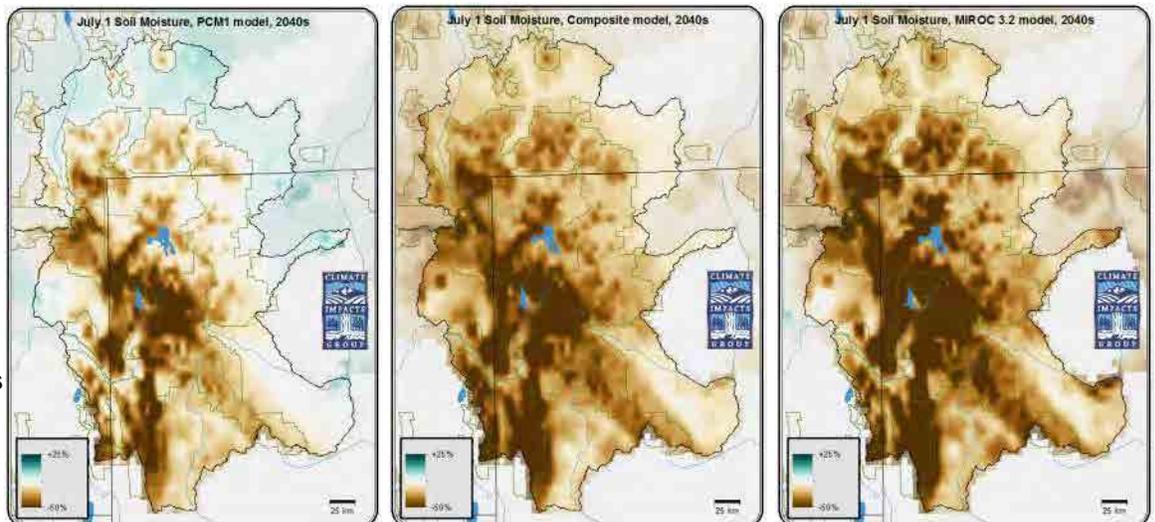
Many of the expected impacts of climate change are because changes in temperature and precipitation interact to affect hydrology. For example, warmer springs contribute to snowpack declines at lower elevations, but at a few (about 1% of the GYA) of the highest places in the GYA, increased spring precipitation could increase snowpack because future temperatures would still be cold enough for the increased precipitation to fall as snow. These changes in turn have consequences for stream flow, ecosystem function and species' biology.



**Projected changes in April 1<sup>st</sup> snowpack for the 2040s in the GYA (left). Scenarios are shown for a climate model that projects warmer, wetter winters (left), the average of 10 climate models (center), and a model that projects very warm, wet winters (right). The average across 10 models is a decline in April 1 SWE of -34% averaged over the GYA.**

To better understand how climate changes are likely to affect hydrology in places as topographically complex as the GYA, hydrologic models can be used to translate increases in temperature and changes in precipitation into hydrologic responses. Hydrologic models use climate along with local information on soils, vegetation, and other conditions to simulate the hydrologic outcomes of climate change. In the GYA, spring snowpack is important in governing streamflow, soil moisture, and habitat for snow-dependent wildlife such as lynx and wolverine. Lower streamflow in late summer also affects habitat quality for resident and migratory fish. Declining snowpack and increasing water balance deficit are therefore likely to affect the region by affecting water availability, plant growth, forest health, fire risk, and wildlife habitat.

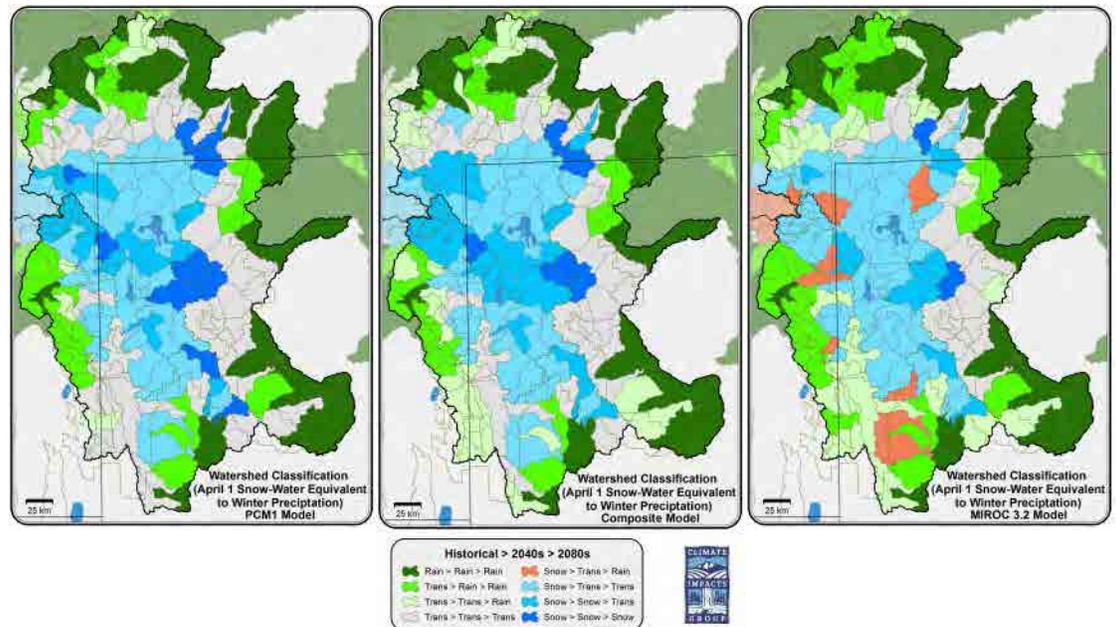
**Projected changes in 2040s A1B July 1 soil moisture in the GYA (right). Scenarios are shown for a climate model that projects warmer, wetter summers (left), the average of 10 climate models (center) and warmer drier summers (right). Averaged over the GYA, projected ensemble mean July 1 soil moisture declines -7% (17mm).**



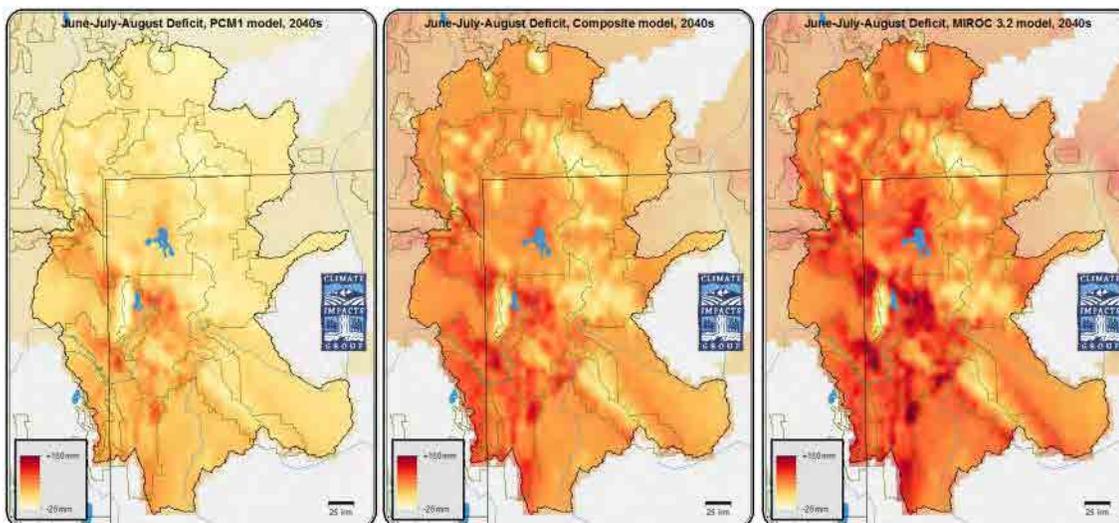
# Projected 21<sup>st</sup> century changes in GYA hydrology

In watersheds where winter precipitation is currently dominated by rain instead of snow, changes in snowpack will not be as profound as “transitional” watersheds where more cool season precipitation currently accumulates as snow. In the highest watersheds, where most cool season precipitation currently falls as snow, temperatures are historically cold enough that watershed hydrology will be less affected by warming until later in the 21<sup>st</sup> century. Below are maps of watershed snowpack vulnerability, defined as “rain dominant” (<10% current cool season precipitation in April 1 snowpack), “transitional” (10% to 40%), and “snow dominant” (>40%). Most transitional watersheds become rain dominant, and all snow dominant watersheds become transient by the 2080s under all three scenarios.

**Projected changes in the ratio of April 1<sup>st</sup> snowpack to total cool season precipitation (Oct. – Mar.) for the 2040s and 2080s in the GYA for a wet climate model (left), the average of 10 climate models (center), and a relatively warm climate model (right). Some watersheds remain transitional, but most historically transitional watersheds become rain dominant and most historically snow dominant watersheds become transitional.**



Forest and grassland responses to climate change are partially determined by the water available to plants given the supply of water (soil moisture from precipitation and snowmelt) and the demand for water by the atmosphere (potential evapotranspiration). Actual evapotranspiration is an estimate of how much water plants use given the supply and demand they experience and other factors specific to different vegetation types. The difference between potential and actual evapotranspiration (PET – AET) is water balance deficit. The larger the deficit, the further from water balance the environment is for plants. Increasing deficit is related to increasing area burned by fire, decreasing tree growth, and increasing vulnerability to forest insects like the mountain pine beetle.



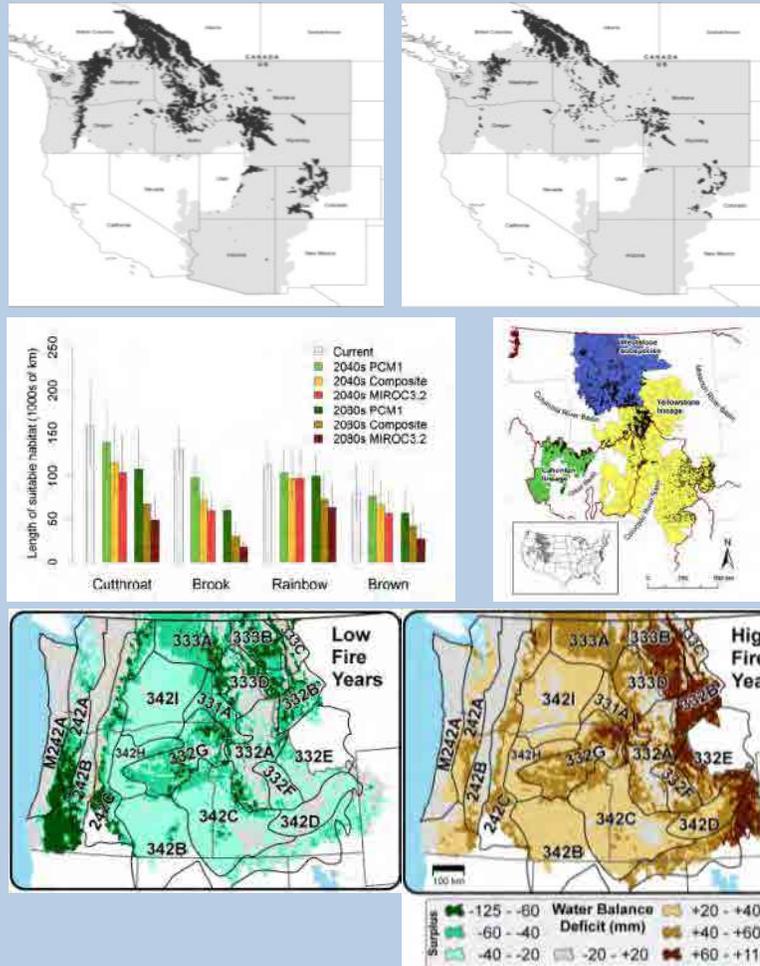
**Projected changes in 2040s A1B summer (JJA) water balance deficit in the GYA (left). Warmer temperatures and decreasing precipitation increase deficit, and most of the increased deficit in the GYE is because potential evapotranspiration is projected to increase. For the 2040s, deficit increases by +31% (+30mm) averaged across the GYA.**

## Climate change impacts on Northern Rockies and GYA ecosystems

The climate change and hydrologic scenarios described in this primer have been used to analyze some potential ecological responses in the western United States and Northern Rockies.

For example, the relationship between spring snowpack and wolverine denning and future snowpack estimates under climate change scenarios were used to show declines (average of 63% by the 2080s compared to historical) in future wolverine habitat and its connectivity<sup>6</sup>. Suitable thermal and flow regimes for cutthroat trout habitat would decline by 58% by the 2080s compared to historical<sup>7</sup>. The relationship between water balance deficit and area burned in the northern Rockies is strong<sup>8,9</sup>, and future changes in deficit suggest large increases in area burned.

The ability to quantify these expected changes depends on identifying the climate and hydrologic mechanisms that drive changes, but the mechanisms are different in each case.



**Top row: Suitable wolverine habitat for historical (left) and 2080s (right) under an ensemble A1B climate scenario<sup>6</sup>. Middle row: Length of suitable stream habitat (left) and map of core population habitat in the 2080s (right) for cutthroat trout<sup>7</sup>. Bottom row: Water balance in low (left) and high (right) fire years, 1980-2009. Deficit is associated with large fire years, particularly in the northern Rockies<sup>8,9</sup>.**

### Citations and notes

- <sup>1</sup> Maximum temperature, minimum temperature, and precipitation trends from raw USHCN and COOP network data were analyzed as part of: Littell, J.S., M.M. Elsner, G. S. Mauger, E. Lutz, A.F. Hamlet, and E. Salathé. 2011. Regional Climate and Hydrologic Change in the Northern US Rockies and Pacific Northwest: Internally Consistent Projections of Future Climate for Resource Management. Project report: April 17, 2011. Latest version online at: [http://cses.washington.edu/picea/USFS/pub/Littell\\_etal\\_2010/](http://cses.washington.edu/picea/USFS/pub/Littell_etal_2010/)
- <sup>2</sup> <http://www.ncdc.noaa.gov/oa/climate/research/cag3/na.html>
- <sup>3</sup> Meehl, G., Covey, C., Delworth, T., Latif, Mojib, McAvaney, B., Mitchell, J., Stouffer, R. and Taylor, K. (2007) The WCRP CMIP3 multi-model dataset: a new era in climate change research Bulletin of the American Meteorological Society, 88 . pp. 1383-1394. Climate model output archived at the CMIP3 archive ([http://www.pcmdi.llnl.gov/ipcc/about\\_ipcc.php](http://www.pcmdi.llnl.gov/ipcc/about_ipcc.php)) was used in this work, which relies on the same models as the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (AR4). See (1) for evaluation of climate models over the upper Columbia, Missouri, and Colorado River basins.
- <sup>4</sup> Nakicenovic, N., and R. Swart, et al. 2000. Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, U.K., 599 pp. Available online at: <http://www.grida.no/climate/ipcc/emission/index.htm>. B1, A1B, and A2 SRES greenhouse gas emissions scenarios are representations of plausible future emissions given assumptions about social and economic global trends. It is important to note that while B1 is always the lowest forcing between 2001 and 2100, A1B has higher greenhouse gas emissions early in the 21<sup>st</sup> century, leading to greater warming under A1B than A2 until the middle of the 21<sup>st</sup> century, after which A2 forcing causes greater warming past about the 2060s.
- <sup>5</sup> <http://www.ncdc.noaa.gov/oa/climate/research/ushcn/>
- <sup>6</sup> McKelvey, K.S., J. P. Copeland, M. K. Schwartz, J. S. Littell, K. B. Aubry, J. R. Squires, S. A. Parks, M.M. Elsner, G.S. Mauger. 2011. Climate change predicted to shift wolverine distributions, connectivity, and dispersal corridors. Ecological Applications, 21(8): 2882–2897.
- <sup>7</sup> Wenger, S.J, DJ Isaak, CH Luce, HM Neville, KD Fausch, JB Dunham, DC Dauwalter, MK Young, MM Elsner, BE Rieman, AF Hamlet and JE Williams (2011) Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. Proceedings of the National Academy of Sciences doi:10.1073/pnas.1103097108.
- <sup>8</sup> Littell, J.S. and R. Gwozdz. 2011. Climatic Water Balance and Regional Fire Years in the Pacific Northwest, USA: Linking Regional Climate and Fire at Landscape Scales. Chapter 5 in McKenzie, D., C.M. Miller, and D.A. Falk, eds. The Landscape Ecology of Fire, Ecological Studies 213, DOI 10.1007/978-94-007-0301-8\_5, © Springer Science+Business Media B.V. 2011.
- <sup>9</sup> McKenzie, D., and J.S. Littell. 2011. Climate change and wilderness fire regimes. International Journal of Wilderness 17(1):22-27, 31.