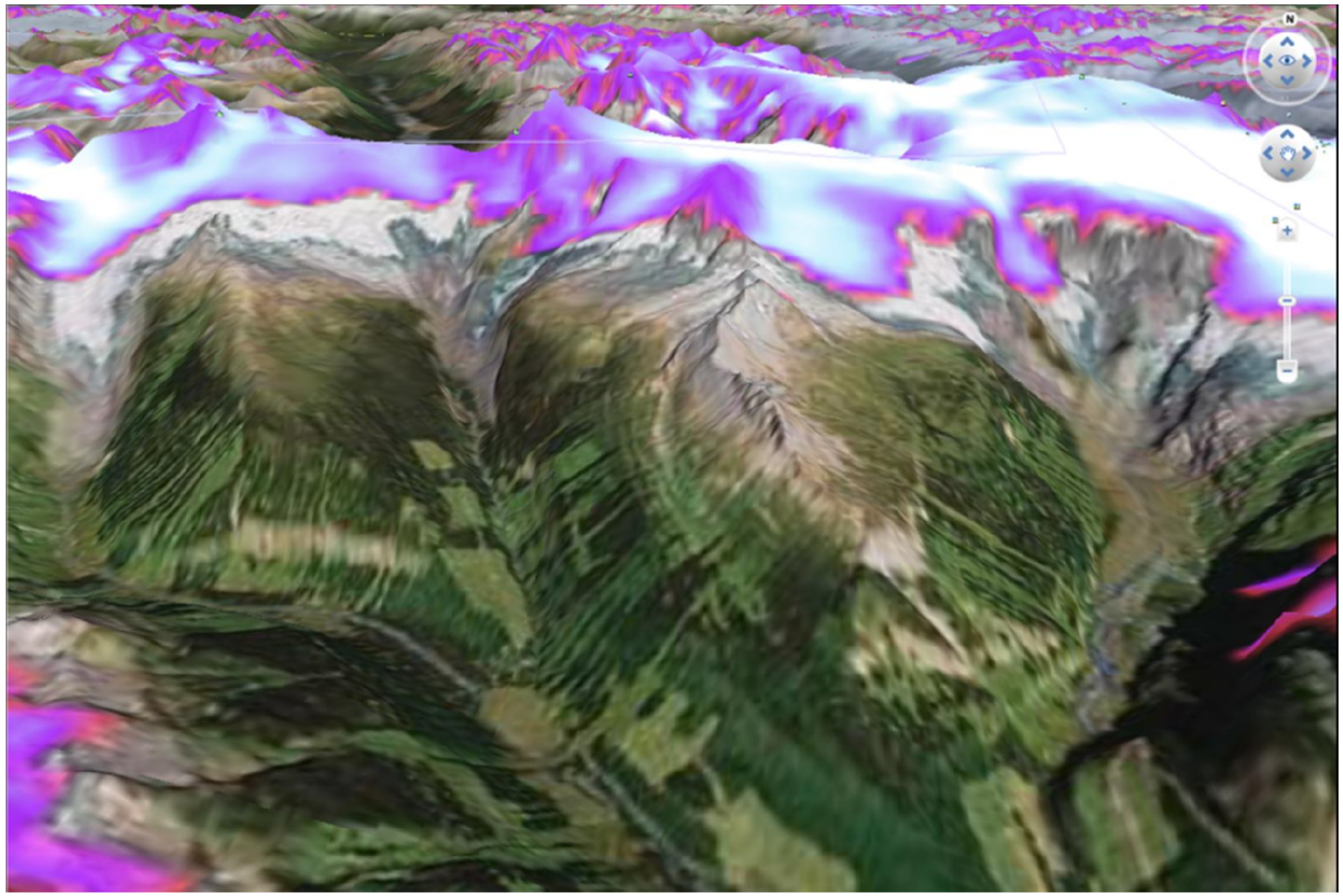
PROJECTED CHANGES IN GLACIER AREA, VOLUME & DYNAMICS

- Ca. 2000
- Model result using CRU & NARR forcing, draped over Google Earth topography



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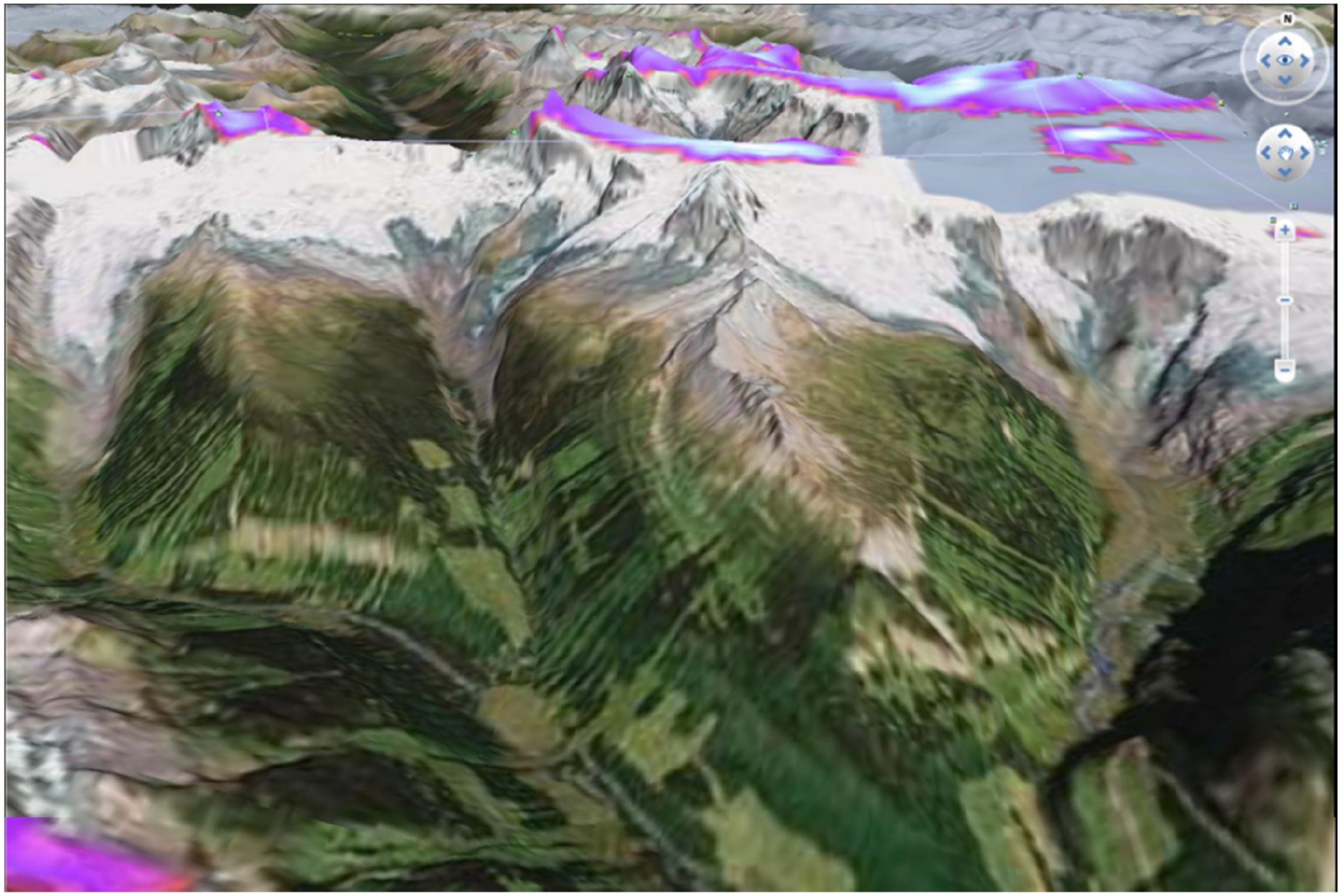
PROJECTED CHANGES IN GLACIER AREA, VOLUME & DYNAMICS

- Ca. 2100
- Model result using MIROh-B1 forcing, draped over Google Earth topography



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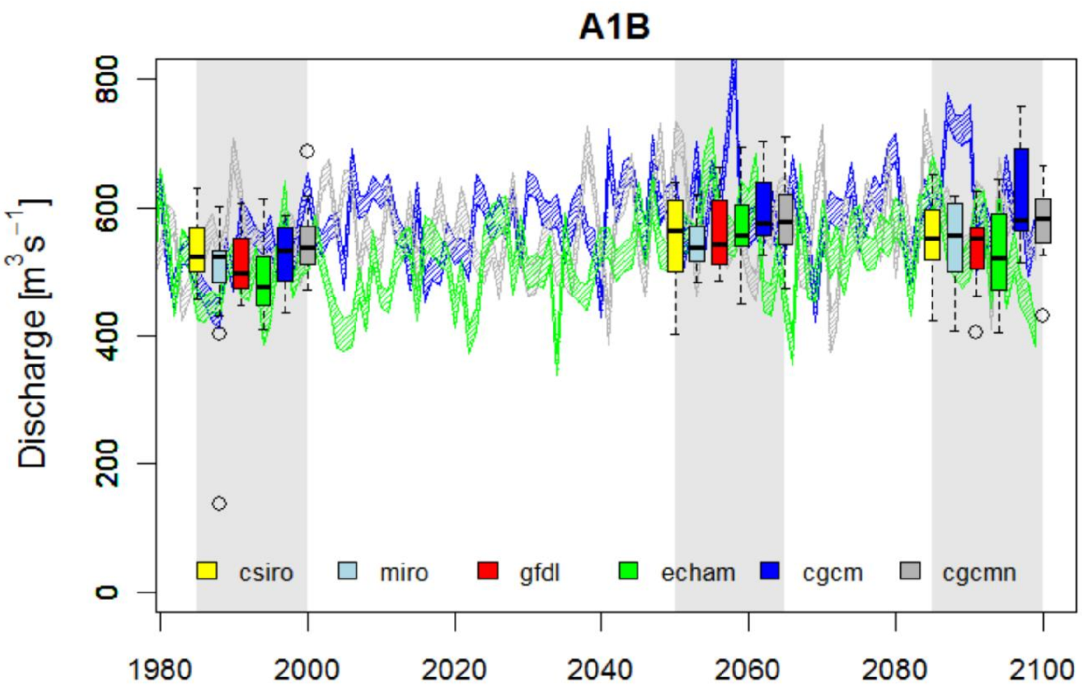
PROJECTED INFLOW TRENDS

TIME SERIES EXAMPLE FOR A1B SCENARIO



Historic values and projected changes in mean annual streamflow during the periods 2050-2065 and 2085-2100 for emission scenario A1B. Boxplots show the interannual variation of each time slice for each GCM, based on the ensemble mean of runs using all 23 behavioural parameter sets. Trajectories of ranges of ensemble predictions are shown for CGCMn (grey), CGCM (blue), and ECHAM (green).

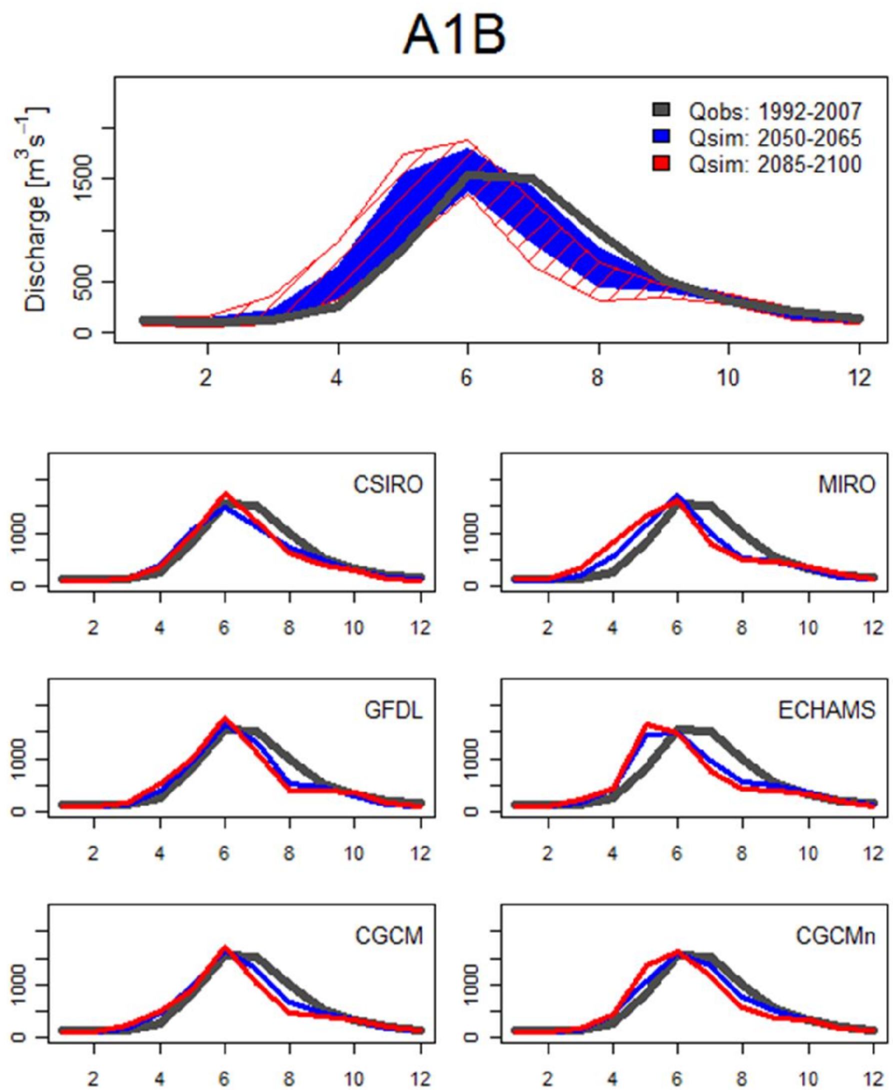
PROJECTED INFLOW TRENDS

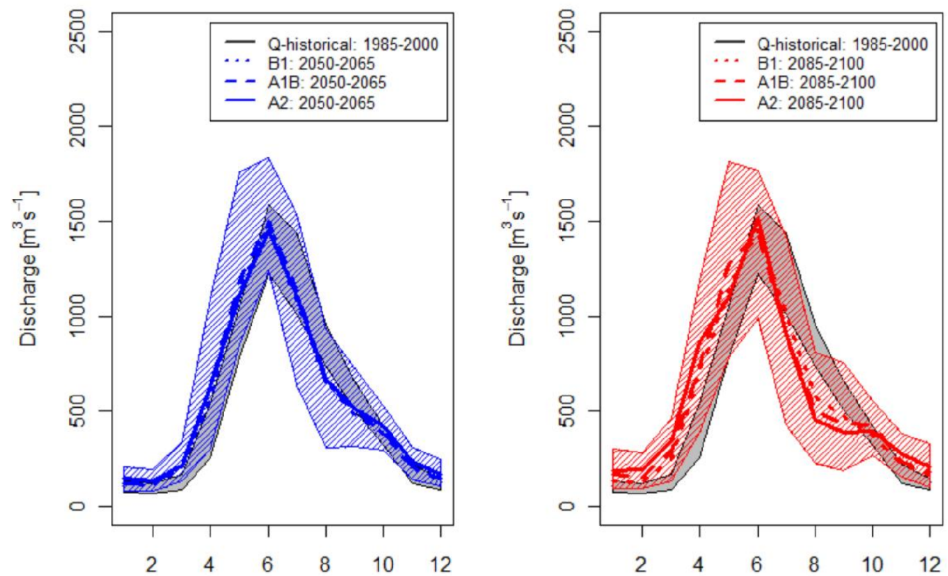
- Likely future flow increase
- Despite decreases in ice melt; increases in precipitation offset higher evapotranspiration rates and lower glacier ice melt
- While precipitation and temperatures are projected to continue to increase from the 2050's to the 2090's, flow volumes will remain fairly unchanged

Mica	mean annual precipitation change* (%)				mean annual temperature change* (ºC)				mean annual flow change* (%)			
SRES	2050-2065		2085-2100		2050-2065		2085-2100		2050-2065		2085-2100	
B1	**+6.3**	-3 to +15	**+10.8**	+7 to +19	**+1.9**	+1 to +3	**+2.6**	+1 to +5	**+4.2**	-2 to +11	**+4.7**	-2 to +11
A1B	**+10.8**	+2 to +16	**+14.5**	+6 to +25	**+2.2**	+1 to +4	**+3.4**	+2 to +6	**+10.0**	+3 to +16	**+8.6**	+3 to +18
A2	**+10.4**	+7 to +19	**+15.3**	+4 to +25	**+2.2**	+2 to +3	**+4.1**	+3.8 to +4.4	**+7.7**	+1 to +19	**+7.6**	-7 to +17
mean	**+9.2**	---	**+13.5**	---	**+2.1**	---	**+3.4**	---	**+7.3**	---	**+7.0**	---

* relative to 1985-2000 baseline

PROJECTED INFLOW TRENDS - SEASONALITY





Historic and projected seasonal streamflow response for 2050-2065 (left) and 2085-2100 (right) time slices. The dashed areas (blue = 2050-2065; red = 2085-2100) cover the range of uncertainties associated with GCMs, emission scenarios and HBV-EC parameter estimation. Solid, dotted, and dashed lines show means for B1, A2, and A1B emission scenario over all GCMs (blue = 2050-2065; red = 2085-2100).

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PROJECTED INFLOW TRENDS - SEASONALITY

- Despite inter-GCM-Scenario variability, there are an unambiguous trends
  - Higher flows during the late fall and winter months (Nov-Feb)
    - Caused by warmer and wetter fall-winter periods and associated increases in the snow:rain ratio
  - Earlier and higher flows in spring and early summer (Mar-May)
    - Caused by warmer springs and larger basin-wide snowpack
  - However, June remains unchanged
  - Lower summer flows (Jun-Sep)
    - Substantial decreases in August flows
    - Caused by (i) an earlier snowmelt freshet, (ii) a decrease in ice melt contributions, (iii) a decrease in summer precipitation and (iv) an increase in ET (in response to higher temperatures)
    - Ice melt contributions to annual runoff decline in all future scenarios
    - With snowmelt occurring earlier in the year, the relative contribution of ice melt to August flows will remain relatively high and may even increase
- Combined effects amount to a hydrologic regime change from nivo-glacial to nival

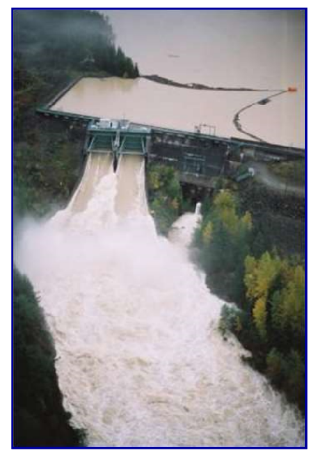
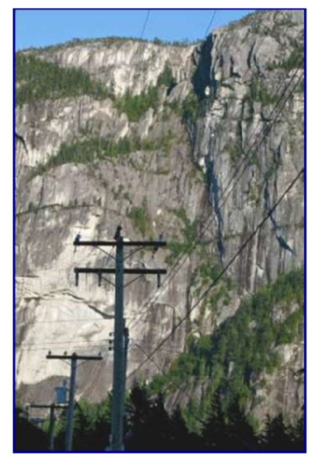
CONCLUSIONS

- The study has included a comprehensive assessment of uncertainties associated with uncertainties in hydrologic parameters, emission scenarios and GCMs
- First study to use glacier area and volume changes to assist hydrologic model calibration in a GLUE-typne approach
- Loss of glacier ice: substantial effect on total annual inflow volume, and thus theoretical generation potential
- But overall picture for Mica is for possibly modest inflow gains due to precipitation increases
- Increased precipitation will outweigh losses due to glacier ice melt reduction
- Seasonal flow patterns will very likely change
- Incorporating glacier change appears necessary for physically plausible climate change impact projections

THANKS FOR LISTENING





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Columbia River Treaty Operating Committee meeting

HYDROLOGIC CLIMATE CHANGE IMPACT
PART 2b: PREDICTIONS – PCIC STUDY

Teleconference: Burnaby, BC, Canada – Portland, OR, USA
August 10, 2011

Frank Weber, Lead, Runoff Forecasting

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CONTENT

PART 2b: PREDICTIONS – PCIC STUDY

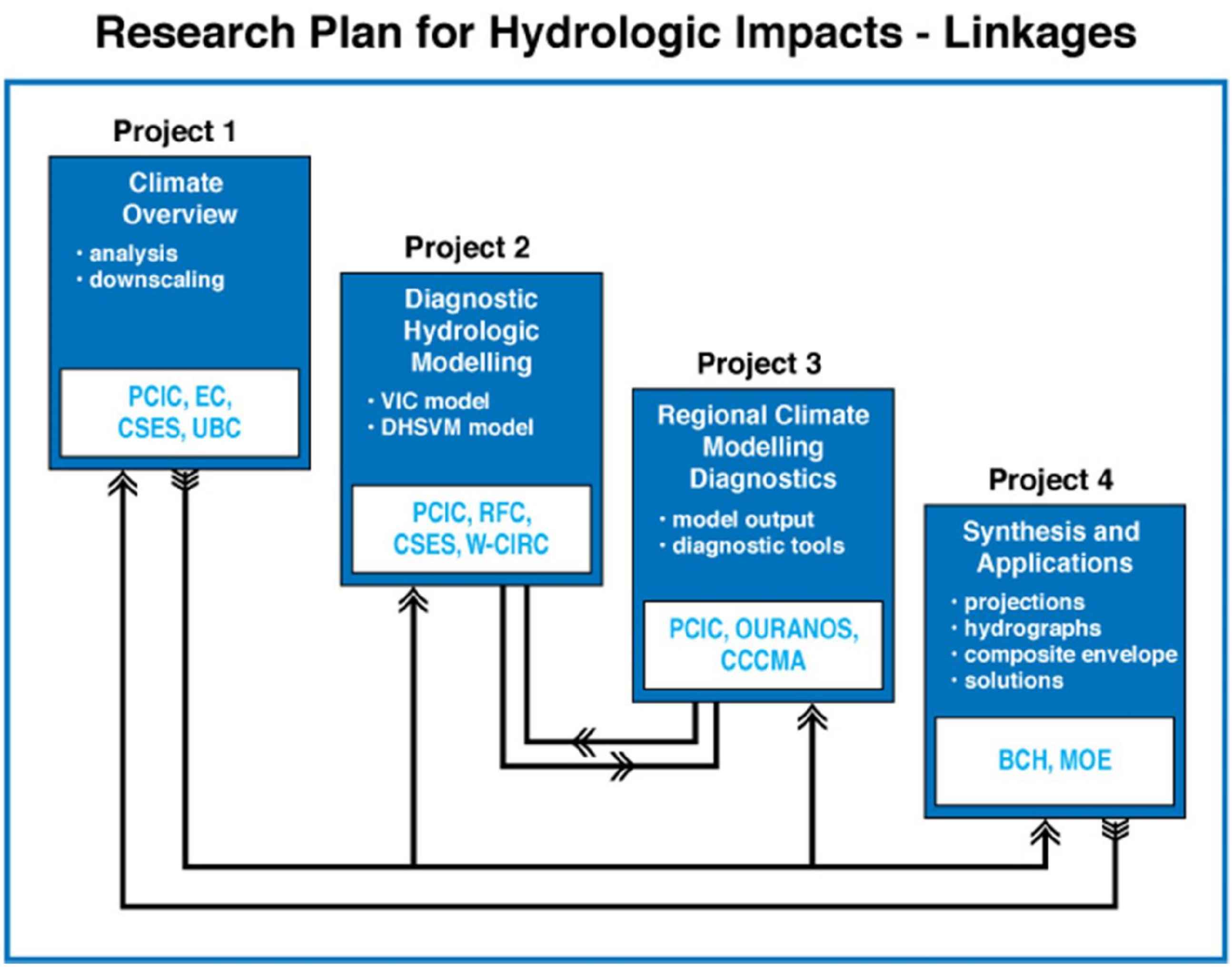
- **Overall modeling approach**
- **Multi-criteria based GCM/Scenario selection**
- **GCM downscaling**
- **Watershed modeling**
- **Columbia glacier mass balance modeling**
- **Projected climate trends**
- **Projected inflow trends**
- **Projected April 1 snow water equivalent trends**
- **Projected glacier mass balance trends**

PCIC HYDROLOGIC IMPACTS STUDY

MOTIVATION & OBJECTIVES

- Provide data sets of local, unregulated inflow that can be used as input to system optimization and reservoir operations modeling
- Provide estimates of future streamflow and inflow conditions at a monthly time-scale
- Report results specifically for the 2050s period (2041-2070)
- For selected regions and watersheds

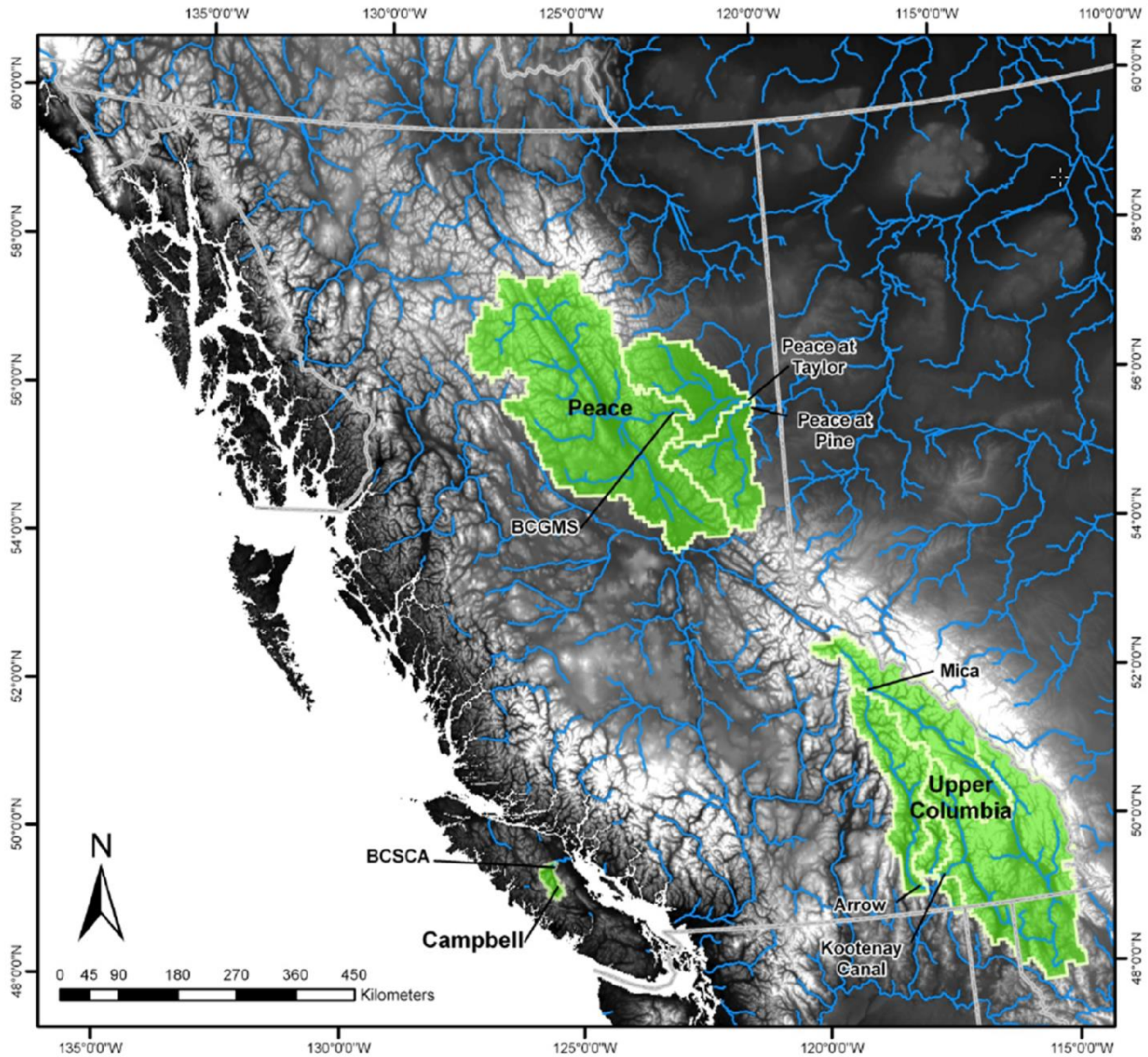
PCIC CLIMATE CHANGE PROGRAM



PCIC HYDROLOGIC IMPACTS STUDY

GEOGRAPHIC SCOPE

- Peace River basin
- Columbia River basin
- Campbell River basin



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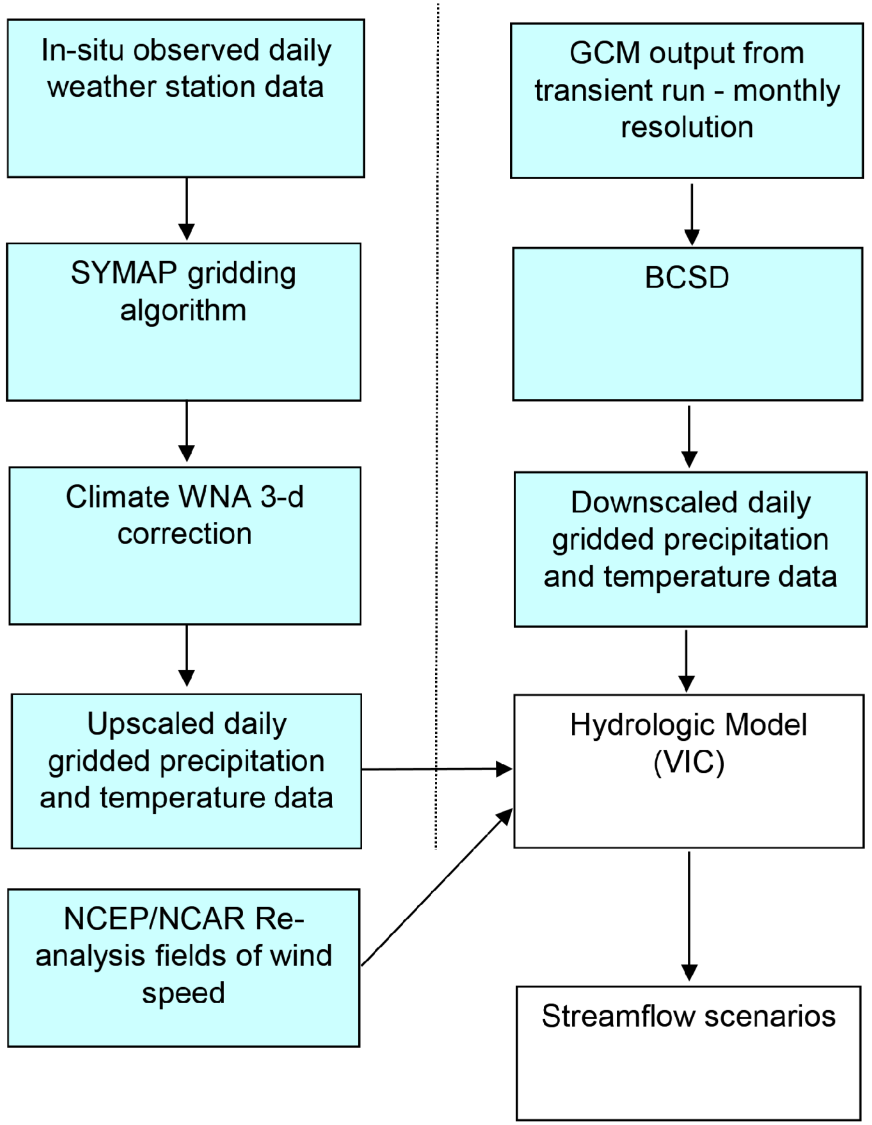
OVERALL MODELING APPROACH

Hydrologic model calibration



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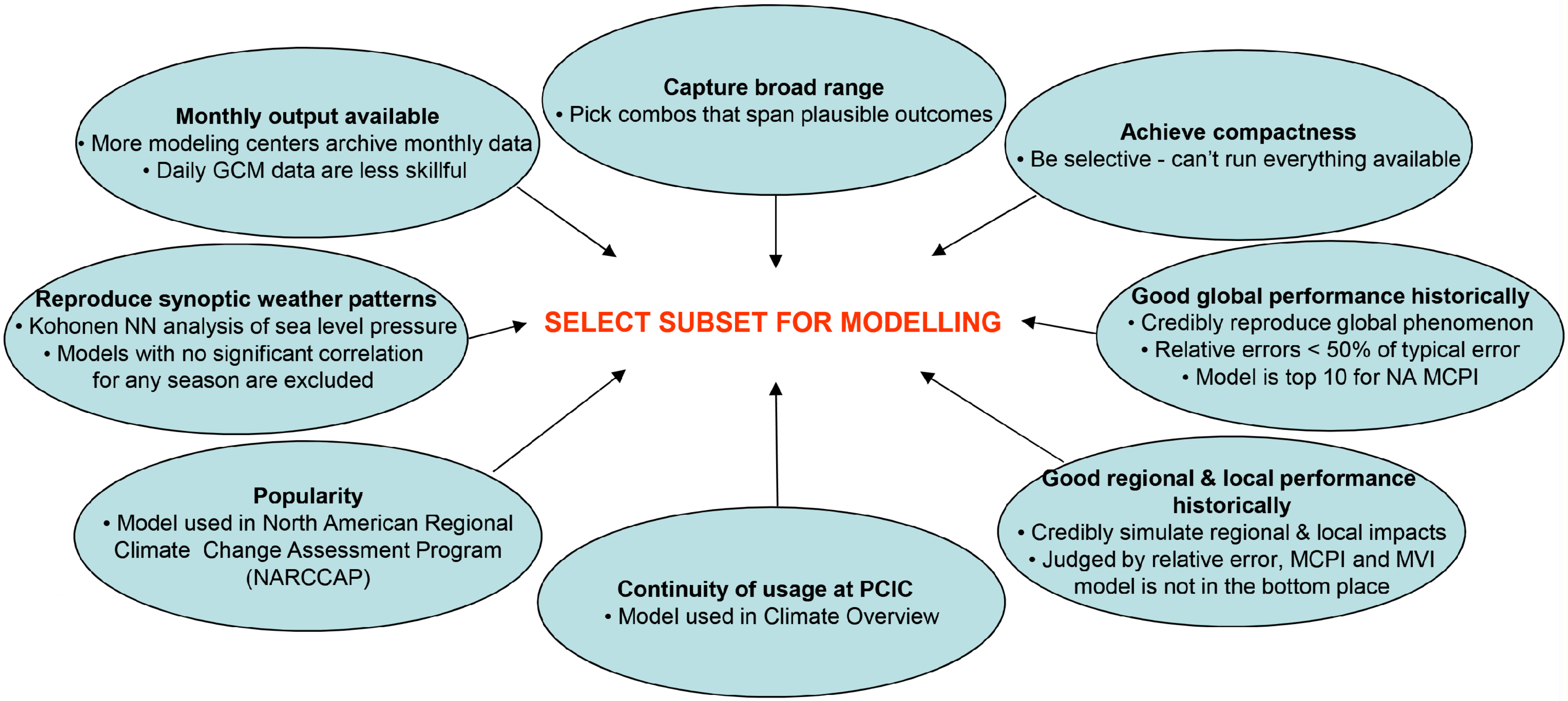
MULTI-CRITERIA BASED GCM-SCENARIO SELECTION

The selection of GCMs depends on the intended application – i.e., there is no universal set of performance metrics that are optimally suited for all applications



MULTI-CRITERIA BASED GCM-SCENARIO-RUN SELECTION

FINAL SELECTION OF 8 GCMs

GCM	B1	A1B	A2
CGCM3.1 (T47)	X (WC^2N)	X (WC^2N)	X (WC^2N)
CGCM3.1 (T63)	(WC^2N)	(WC^2N)	(WC^2N)
CSIRO-Mk3.0	X (WC^2N)	X (WC^2N)	X
CCSM3	X	X	X
GFDL-CM2.0	(WC^2N)	(WC^2N)	(WC^2N)
GFDL-CM2.1	X	X	X
MIROC3.2 (hires)	(WC^2N)	(WC^2N)	
MIROC3.2 (medres)	X	X	X
ECHAM5/MPI-OM	X (WC^2N run 1)	X (WC^2N run 4)	X (WC^2N run 1)
UKMO-HadCM3	X	X	X
UKMO-HadGem1	NA	X	X

GCM DOWNSCALING FOR WATERSHED MODELING

BIAS CORRECTED SPATIAL DISAGGREGATION (BCSD)

- 3 Step procedure:
  1. Bias correction of monthly GCM temperatures & precipitation through percentile mapping
  2. Spatial downscaling by interpolating anomalies via simple scaling of large scale data
  3. Temporal downscaling to daily resolution by randomly resampling the historical record and adjusting the temperature and precipitation sequences to match the monthly GCM projection
- Results in a transient time series of climate forcings
- Daily characteristics do not reflect the changes to the statistical properties of daily weather projected by GCMs
- For example, the frequency of dry and wet days and relative frequency of individual weather patterns in unrelated to that projected by the GCMs

WATERSHED MODELING

- VIC: good track record for flow/climate change simulations on global river systems, Columbia River basin and the mountaineous western United States.
- Spatially-distributed (gridded) macro-scale watershed model
  - Applied at a resolution of 1/16º (app. 27-31 km2)
  - Occurrence and change in glacier mass is mimicked using snow process modeling
- Generally 1990-1995 calibration period (w/ 1995 glacier cover); Upper Columbia 1990-1994; validation against 1985-1989 streamflow
- Calibration to 23, 1 and 24 subbasion stramflow records in the Peace, Campbell and Columbia areas
- Calibration with the automated multi-objective Complex Evolution optimization method
- 1 parameter set was chosen from the Pareto set to balance Nash-Sutcliffe efficiency, log Nash-Sutcliffe efficiency and percent volume bias
- Good models, but Columbia models generally undersimulate streamflows
- Process-oriented streamflow model to convert future climates into flow realizations for 1995 to 2098 period
- Force model forward under downscaled (BCSD) projected future climate

WATERSHED MODEL QUALITY

Summary of calibration and validation results for Columbia River sub-basins for three performance measures. *NS* is Nash-Sutcliffe, *LNS* is Nash-Sutcliffe of log-transformed discharge, and *%VB* is percent volume bias. Project sites are indicated with bold text.

Basin	Calibration 1990-1994			Validation 1985-1989		
	NS	*LNS*	*%VB*	*NS*	*LNS*	*%VB*
BCHAR[#$]	**0.78**	**0.84**	**-2**	**0.80**	**0.65**	**-8**
BCHDN[#]	**0.65**	**0.54**	**-7**	**0.73**	**0.59**	**-8**
BCHKL[#†]	**0.67**	**0.60**	**-7**	**0.72**	**0.74**	**4**
BCHMI[#]	**0.89**	**0.83**	**-9**	**0.88**	**0.79**	**-7**
BCHRE[#$]	**0.97**	**0.97**	**-4**	**0.92**	**0.81**	**-10**
BCWAT[#]	**0.76**	**0.75**	**-10**	**0.74**	**0.67**	**-12**
BLAAW	0.72	0.86	10	0.75	0.87	-3
BULNW	**0.83**	**0.77**	**-4**	**0.81**	**0.72**	**-17**
COLAD	0.94	0.94	-2	0.91	0.88	-1
ELKAF	0.99	0.97	-3	0.81	0.69	-13
ELKNN	0.89	0.92	-3	0.75	0.77	-8
FORAM	0.66	0.70	-6	0.72	0.74	-1
KICAG	0.77	0.87	-8	0.77	0.86	-2
KOOAF	0.99	0.99	3	0.85	0.80	-4
KOOAK	0.78	0.77	-4	0.75	0.68	17
KOOCF	0.91	0.91	-4	0.84	0.86	-4
KOONS	0.98	0.99	0	0.85	0.83	-6
MICBN	0.75	0.80	-5	0.76	0.79	-15
PALIL	0.80	0.77	-4	0.80	0.80	-10
SALNS	**0.74**	**0.27**	**-15**	**0.73**	**0.38**	**-12**
SLONC	**0.78**	**0.66**	**-2**	**0.78**	**0.72**	**-2**
SPINS[‡]				**0.67**	**0.82**	**-1**
STMAW	0.99	0.99	-2	0.84	0.63	-16
STMNM	0.76	0.46	-10	0.82	0.47	-20
BCHLB[#&]	0.97	0.93	-1			
Average	0.83	0.80	-4	0.79	0.73	-7

[#] Calibrated and validated to naturalized discharge (see text)
[$] Validation based on monthly streamflow (see text)
[†] Validation based on monthly streamflow over 2003 to 2006 (see text)
[‡] Uncalibrated; validation based on 1980 to 1984 period
[&] Calibrated based on 2003 to 2006 period

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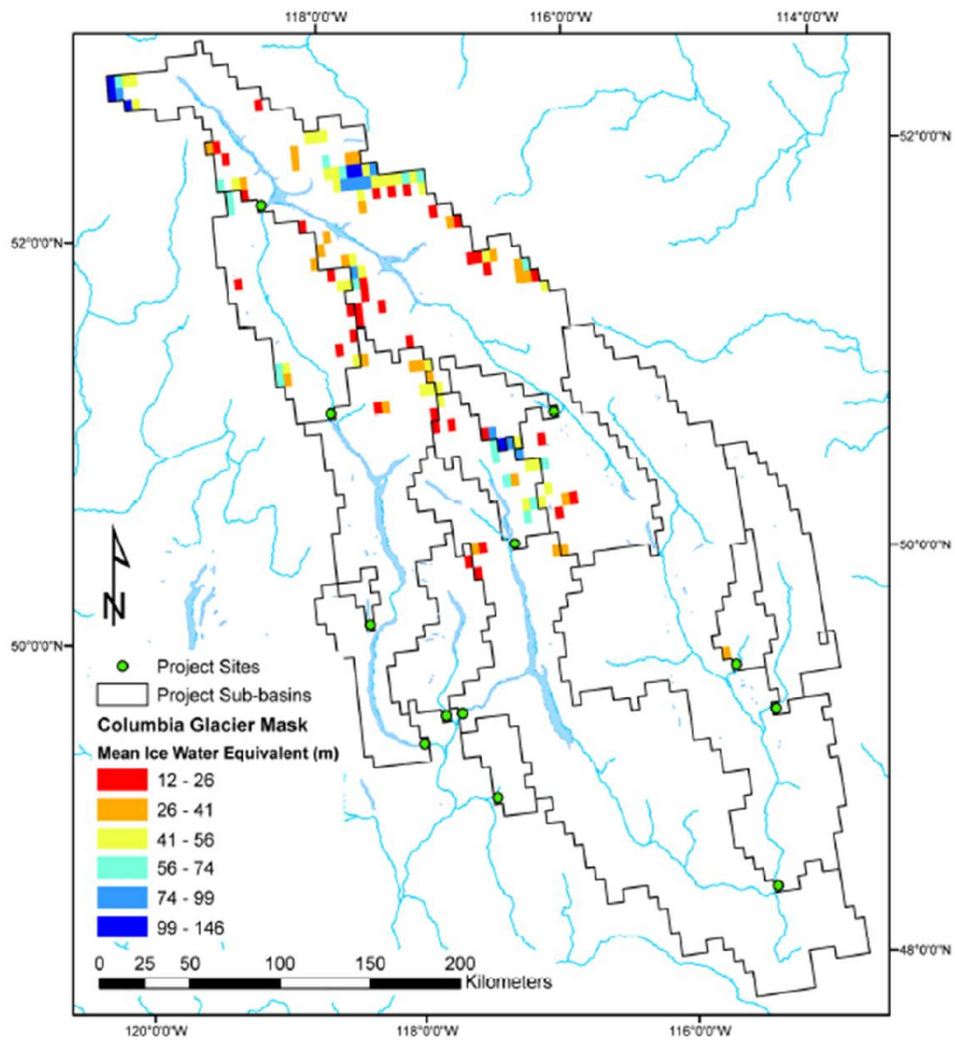
COLUMBIA GLACIER MASS BALANCE MODELING

- Conceptual representation of glacier mass balance into VIC using snow process algorithms, but no explicit representation of glacier dynamics
  - Within VIC modeling tile static glacier cover
  - But across the basin tiles glacier cover is non-static
- Specific VIC cells are designated as glaciated; 1995 glacier extent is then converted to ice water equivalent using empirical volume-area scaling relationships and literature values of ice density
- Caveats: model cannot isolate seasonal snow versus glacier runoff and cannot introduce separate albedo functions for snow and ice
- Due to data limitations, 1950-2098 model runs were initialized with 1995 glacier mass in 1950 for tracking run, and then again in 1995 for forecast run



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PROJECTED CLIMATE TRENDS

- Consistent signal across scenarios, GCMs and seasons that temperatures will increase
- Less consistent pattern for an increase in precipitation, i.e., the range of individual GCM projections includes both positive and negative changes

	median annual precipitation* (%)	median annual temperature* (ºC)
SRES	Columbia region	
B1	+10	+1.8
A1B	+7	+2.7
A2	+5	+2.3
mean	+7.3	+2.3

* relative to 1961-1990 baseline

PROJECTED CLIMATE TRENDS

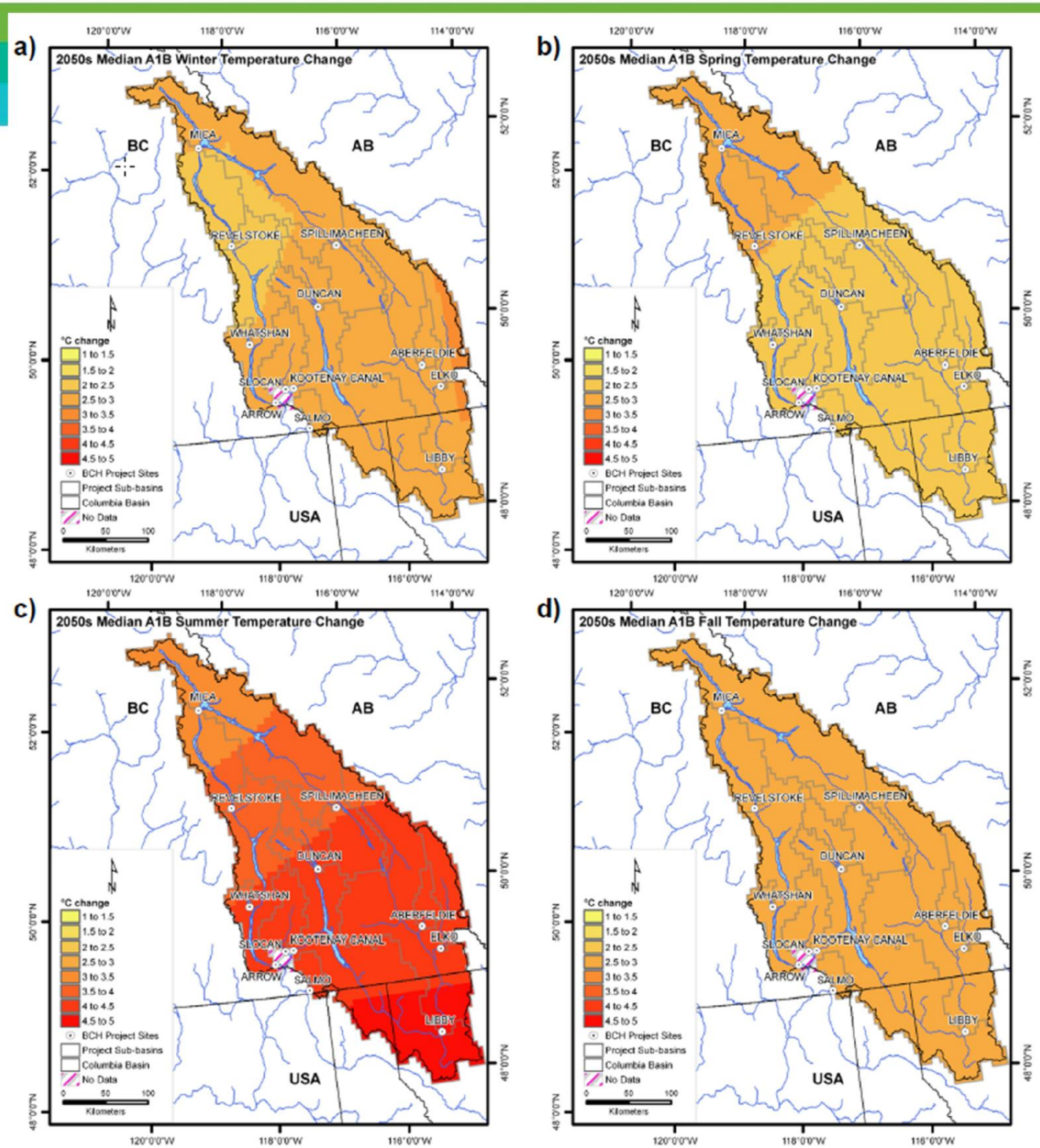
MICA BASIN – MEDIAN CHANGE* IN THE 2050s

		Annual	Winter	Spring	Summer	Fall
B1	Temperature (°C)	2.0	2.6	2.0	2.0	1.6
	Precipitation (%)	9	9	16	-4	12
A1B	Temperature (°C)	2.7	2.6	2.6	3.5	2.7
	Precipitation (%)	10	17	16	-10	17
A2	Temperature (°C)	2.2	2.6	1.9	3.1	2.0
	Precipitation (%)	7	10	16	-9	9

* relative to 1961-1990 baseline

PROJECTED CLIMATE TRENDS

2050s TEMPERATURE A1B SCENARIO



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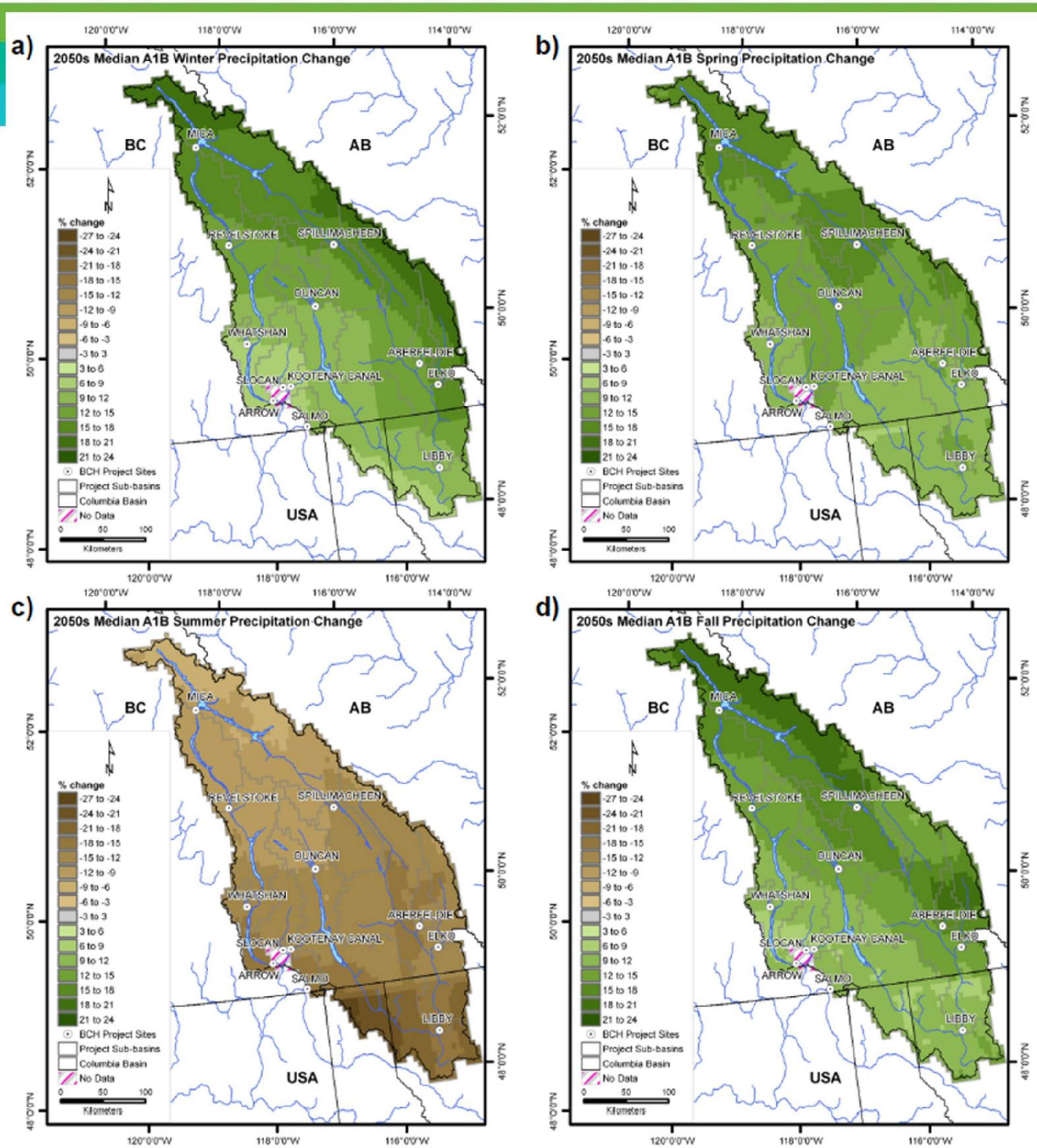
PROJECTED CLIMATE TRENDS

2050s PRECIPITATION

A1B SCENARIO



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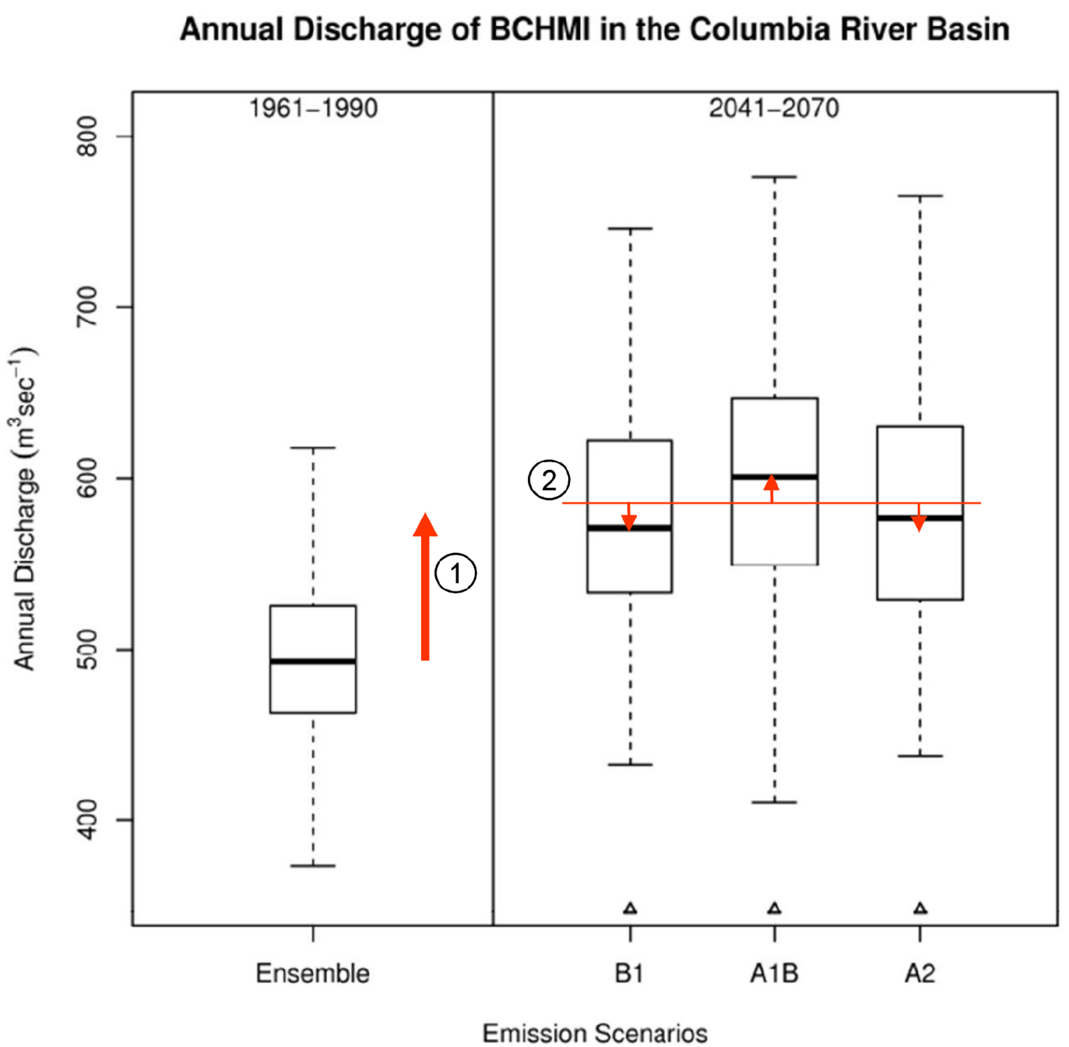
PROJECTED TRENDS IN ANNUAL INFLOW VOLUME

MICA



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PROJECTED TRENDS IN ANNUAL INFLOW VOLUME

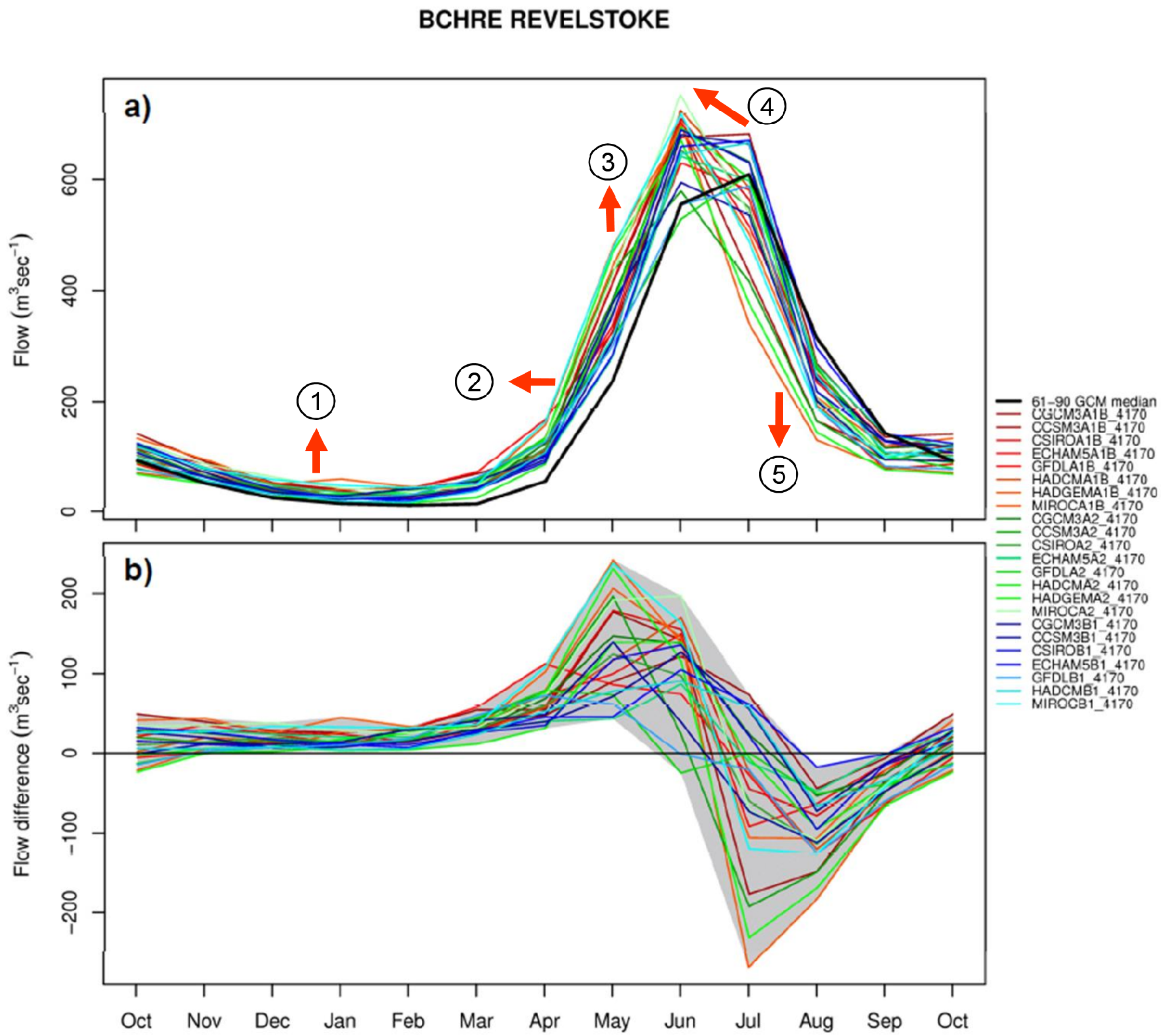
1. Annual flow is projected to increase at the majority of the project sites
2. Differences between scenarios are smaller than the combined inter-annual and inter-GCM differences

	median annual precipitation* (%)	median annual temperature* (ºC)	median annual flow* (%)				
SRES	Columbia region		MCA	REV	ARD	DDM	KLK
B1	+10	+1.8	+16	+13	+12	+13	+12
A1B	+7	+2.7	+22	+17	+16	+18	+13
A2	+5	+2.3	+17	+10	+8	+12	+7
mean	+7.3	+2.3	+18	+13	+12	+14	+11

* relative to 1961-1990 baseline

PROJECTED TRENDS IN MONTHLY INFLOWS

REVELSTOKE



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PROJECTED TRENDS IN MONTHLY INFLOWS

1. Slightly increased late fall and winter flows (Nov-Feb)
2. Earlier freshet onset
3. Substantially higher spring and early summer flows (Mar-Jun)
    - Increased winter snow accumulation and melt
    - Higher spring temperatures
    - Wetter spring
4. Some indication of an advance of the month of peak flows & higher monthly peak flows
5. Substantially lower late summer and early fall flows (Jul-Sep)
    - Presumably increased evaporation
    - Decreased precipitation
    - Changes in glacier runoff

- Projection uncertainty predominantly from GCMs
- Median monthly flow projection for the 2050s largely insensitive to emission scenarios