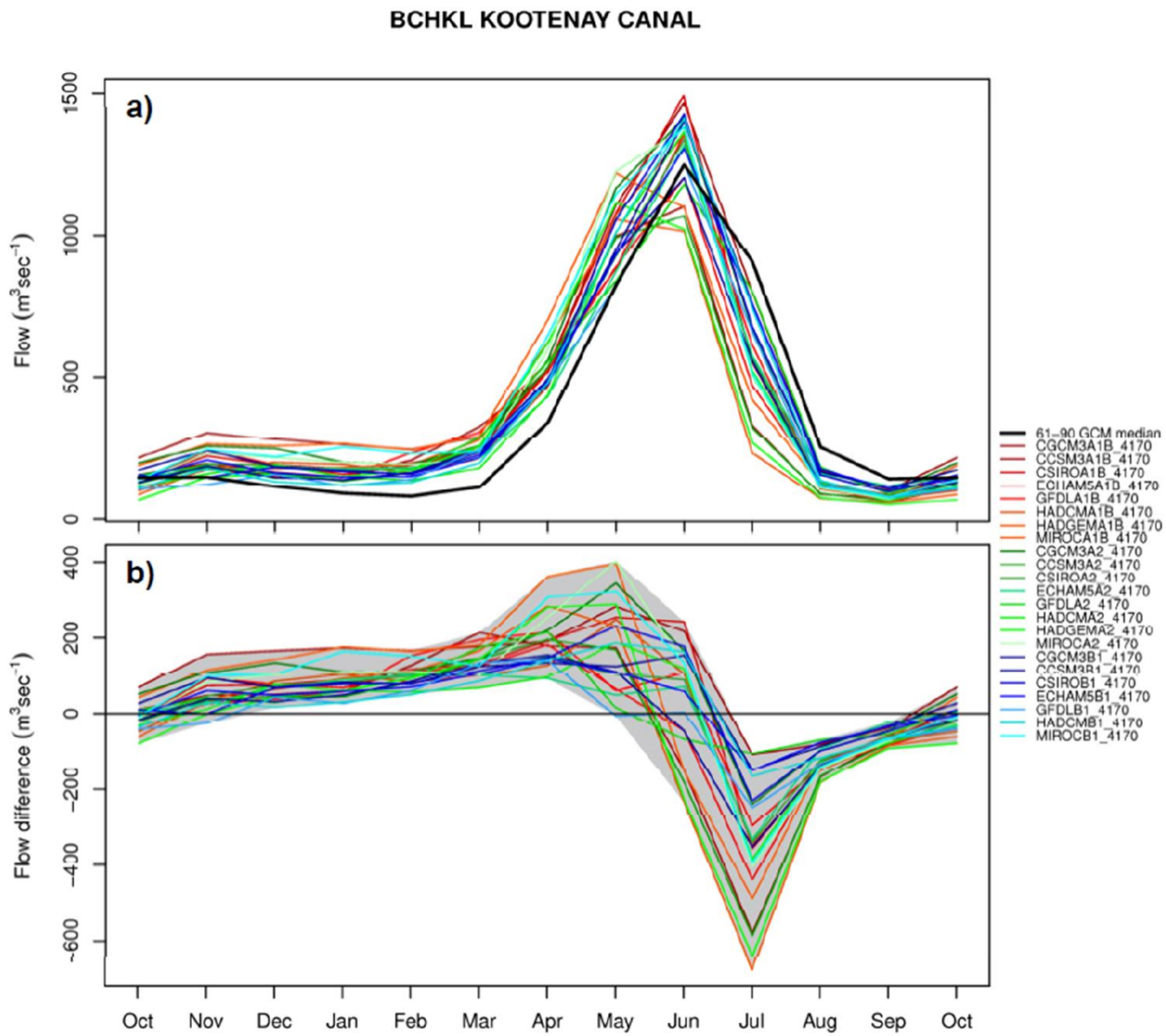
PROJECTED TRENDS IN MONTHLY INFLOWS

KOOTENAY LAKE



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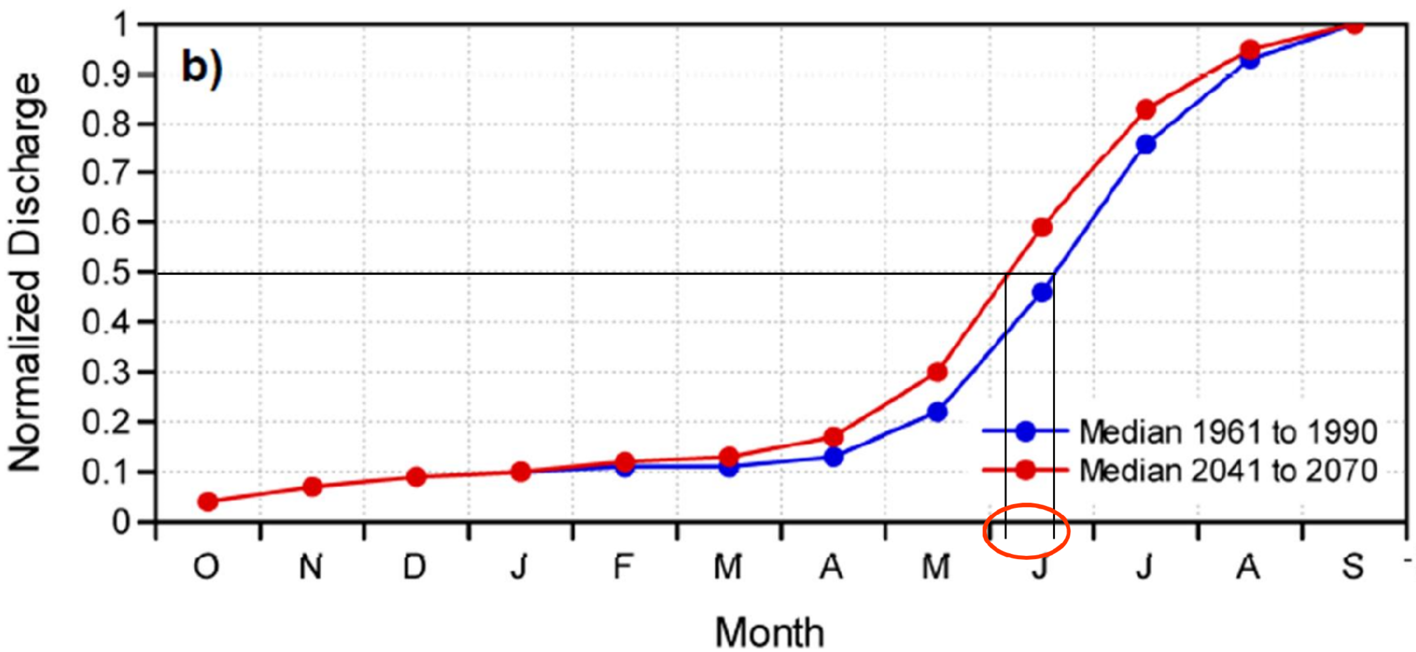
PROJECTED TRENDS IN SEASONAL INFLOW VOLUMES

- More runoff is expected to occur earlier in the water year, for example:
  - Half the volume will have run off ~1/2 month earlier for Mica
  - 52% more volume will accumulate from Oct-Jun in the 2050s compared to 1961-1990

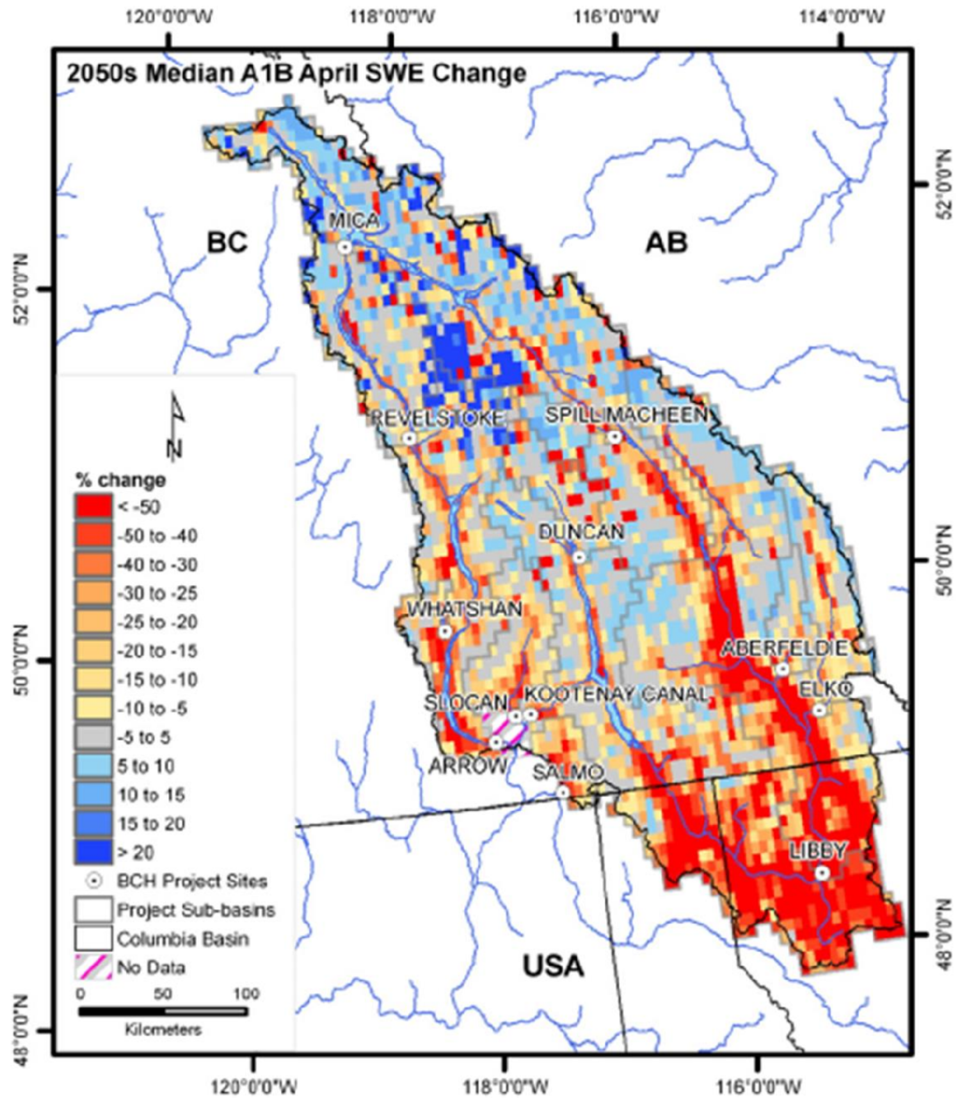


Cumulative median A1B historic and future monthly discharge over the water year (October through September) for the Columbia River at Mica Dam (BCHMI)

PROJECTED TRENDS IN APRIL 1 SWE

Median A1B April 1 SWE anomaly

- North-south and vertical gradient
- In absolute terms A1B median 2050s anomaly of April 1 SWE is (only) -30 mm
- SWE decreases at low elevations are offset by increases at high elevations
- Snow covered area will likely decrease



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PROJECTED TRENDS IN GLACIER MASS BALANCE

- Over the 1995-2070 period cumulative mass balance is -2.3m, -0.4m, +6.3m for A1B, A2, and B1 scenarios, respectively
- Projected depletion rates are substantially slower (and opposite in the case of B1) than trends observed over recent decades
- Glacier extent will shrink by ~50% by the 2050s
- Lack of glacier dynamics in the VIC Model may cause the glacier mass loss to be underestimated and the area loss to be overestimated

Conclusions

- Annual inflow is projected to increase at all Columbia River basin project sites – and in some basins substantially - due to higher precipitation
- Seasonality of inflows will very likely change
- 2050s projections of annual discharge are relative insensitive to the 3 emission trajectories

KEY SCIENCE QUESTIONS

GLACIER-SPECIFIC

- ✓ What will be the net impact of climate and glacier change be on river flows?
- ✓ Should wide-spread glacier recession continue, would likely future increases in precipitation offset decreases in ice melt generation?
- ✓ How do we develop and apply computational tools to generate projections of future glacier coverage & streamflow given a large range of future climate scenarios?
- ✓ How important is it to model these processes interactions in detail?

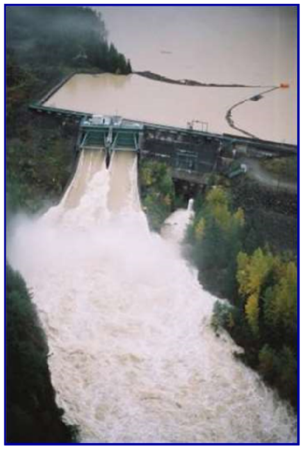
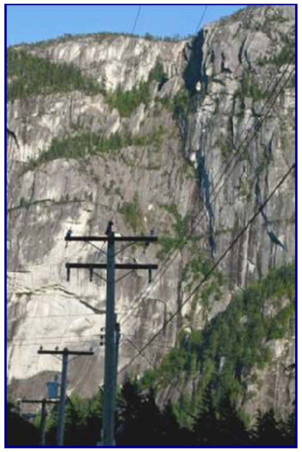
TOTAL WATER SUPPLY

- ✓ What future water supply can we expect for individual projects
- & collectively for the system?
- ✓ What is the direction and magnitude of change?
- ✓ How will the seasonal timing of inflows change?
- Can we expect changes in reliability, i.e., year-to-year variability, of water supply?
- ✓ What is the largest source of uncertainty in the modeling chain?
- How sensitive is hydroelectric power generation to the hydrologic impacts of climate change?

THANKS FOR LISTENING





Columbia River Treaty Operating Committee meeting

CLIMATE CHANGE

PART 1: CLIMATE CHANGE - STATE OF KNOWLEDGE
PART 2: TRENDS IN OBSERVED TIME SERIES

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

Frank Weber, Lead, Runoff Forecasting
Sean Fleming, now: Environment Canada

BChydro
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CONTENT

PART 1: CLIMATE CHANGE - STATE OF KNOWLEDGE

- Key Science Questions
- Definitions
- Climate Variability and Change

PART 2: TRENDS IN OBSERVED TIME SERIES

- Climate Change impact assessments
- Motivation for empirical trend analysis
- Historical hydroclimatic trends – a broadscale assessment
  - Temperature
  - Precipitation
  - Seasonal maximum snowpack
  - Glaciers
  - Inflow

PART 2a: PREDICTIONS – WC^2N STUDY

PART 2b: PREDICTIONS – PCIC STUDY

PART 3: MULTIAGENCY PREDICTIONS - SYNTHESIS

INTRODUCTION

CLIMATE, GLACIERS, SNOWPACK, EVAPOTRANSPIRATION, RIVERS, AND BC HYDRO

- Climate variability & oscillations & change influence river flows
- BC Hydro is an electric utility obtaining the vast majority of its power from hydroelectric generation
- Projected future climatic changes may affect not only demand (heating/cooling) but also supply

INTRODUCTION

KEY SCIENCE QUESTIONS

- What future water supply can we expect for individual projects & collectively for the system?
- What is the direction and magnitude of change?
- How will the seasonal timing of inflows change?
- Can we expect changes in reliability, i.e., year-to-year variability, of water supply?
- What is the largest source of uncertainty in the modeling chain?
- How sensitive is hydroelectric power generation to the hydrologic impacts of climate change?

DEFINITIONS

Climate is what you expect (but also the characteristic range of variability of those conditions), weather is what you get

Climate change (according to the IPCC) refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent ***anthropogenic changes in the composition of the atmosphere*** or in ***land use***.

Climate variability (according to the IPCC) refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

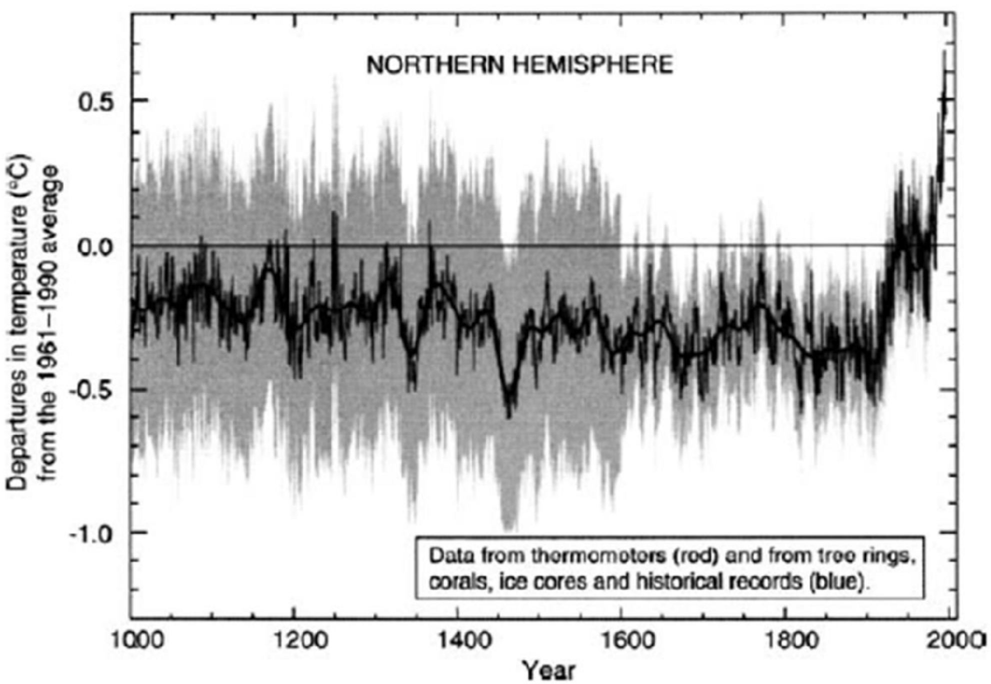
- Commonly climate variability refers to persistent natural changes in the ocean-atmospheric system, that are marked by shifts in the location and/or intensity of the semi-permanent high- and low-pressure cells and that lead to changes in predominant storm tracks.
- Examples are the El Niño/Southern Oscillation, Pacific Decadal Oscillation, Arctic Oscillation and North Atlantic Oscillation

CLIMATE VARIABILITY AND CHANGE

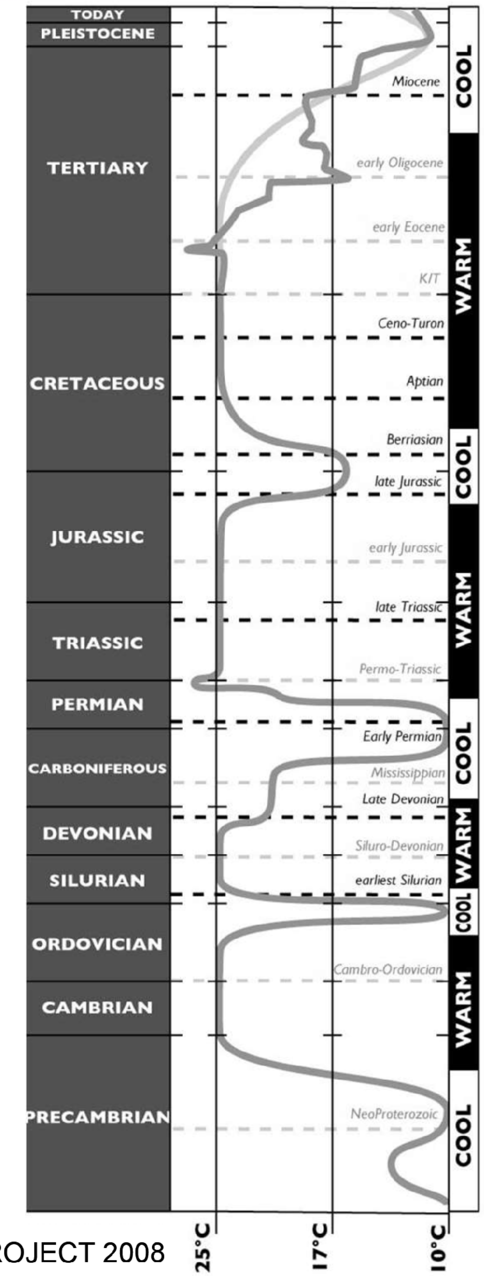
The Earth's climate has changed throughout geologic and historic time:

Attribution Problem

CLIMATE VARIABILITY AND CHANGE



IPCC. 2001a. Northern Hemisphere average annual surface air temperature variations over the last millennium from proxy, historical and instrumental observations (IPCC, 2001a). Smoother version of NH series and two standard error limits (gray shaded) are shown.



PALEOMAP PROJECT 2008

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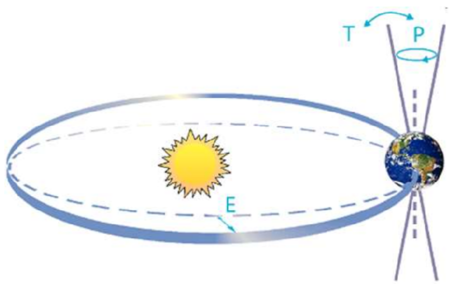
CLIMATE VARIABILITY AND CHANGE

NATURAL VARIATIONS & OSCILLATIONS ON A WIDE RANGE OF TIME SCALES

- Variations in astrophysical forcings (i.e., solar output)
- For at least the last 2.5 million years (i.e., from the beginning of the Pleistocene epoch) glacial and interglacial periods have alternated on app. a 100,000-year cycle, the Milankovitch Cycle, which is the result of the varying congruence of three cycles (eccentricity, obliquity/tilt and precession)

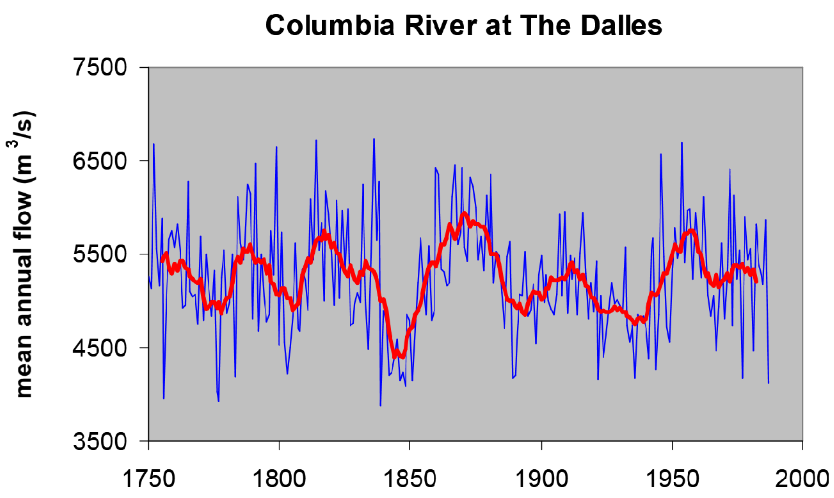


- Atmospheric carbon dioxide (CO_2) provides positive feedback to warming and cooling. CO_2 concentration is low in the cold glacial times (~190 ppm), and high in the warm interglacials (~280 ppm)
- Variations in the CO_2 levels due to tectonic activity
- Changes in ocean circulation and heat transport can explain many features of abrupt events

CLIMATE VARIABILITY AND CHANGE

NATURAL VARIATIONS & OSCILLATIONS ON A WIDE RANGE OF TIME SCALES

- El Niño-Southern Oscillation
- Pacific Decadal Oscillation
- Long-term persistence/Hurst/fractal effects
- Other geophysical (e.g., volcanic) forcings
- Astrophysical (e.g., orbital, solar) forcings



Data from Gedalof et al., *J. Am. Water Resour. Assoc.*, 2004

CLIMATE VARIABILITY AND CHANGE

LONG-TERM ANTHROPOGENIC CLIMATE CHANGE

- Attribution problem intends to establish whether recent climate change is natural or anthropogenic
  - Process-based approach: without anthropogenic forcing, current climate change cannot be explained plausibly (argumentation used by IPCC)
  - Statistical approaches: e.g., nonparametric testing of variability and trend
- Requires advances in scientific knowledge
- Population & economic growth → fossil fuel combustion & deforestation → intensified greenhouse effect
- Observed global warming trend in the modern time series cannot be adequately explained by natural agents of variability

Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic GHG concentrations.[7] It is *likely* that there has been significant anthropogenic warming over the past 50 years averaged over each continent (except Antarctica) (Figure SPM.4). {2.4}

From IPCC (Climate Change 2007: Synthesis Report)

CLIMATE CHANGE IMPACT ASSESSMENTS

MULTI-THREAD ASSESSMENT OF CLIMATE CHANGE IMPACTS

- Hydrology & Technical Services Group has undertaken studies to assess water supply implications
- The goal is to support long-term system planning & optimization by other BC Hydro groups
- Large & complicated problem with no standard engineering/geoscience code of practise
- To address hydrologic climate change impact questions, BC Hydro formed a partnership with the Pacific Climate Impacts Consortium (PCIC) and the Western Canadioan Cryospheric Network (WC2N)
- Brought together some of the world's leading scientists in climatology, glaciology, and hydrology
- Funded targeted R&D
    - $800k to PCIC for 2007-2010 & $1.3m for 2011-2014
    - $127k to WC2N

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PACIFIC CLIMATE IMPACTS CONSORTIUM

WC2N WESTERN CANADIAN CRYOSPHERIC NETWORK

hydrology & technical services

CLIMATE CHANGE IMPACT ASSESSMENTS

MULTI-THREAD ASSESSMENT OF CLIMATE CHANGE IMPACTS

- Prudent to pursue several scientific lines of inquiry in parallel
- Don’t keep all your eggs in one basket:

Pacific Climate Impacts Consortium (PCIC)
Multi-watershed modeling study
BC-wide hydroclimatic trend analysis

Western Canadian Cryospheric Network (WC^2N)
Modelling study of coupled glacier & hydrologic change in a test basin

University of Washington (UW) & River Management Joint Operating Committee (RMJOC)
Multi-watershed modeling study
Development of planning data sets

BC Hydro
Time series analysis of historical reservoir inflows

EMPIRICAL ANALYSIS OF HYDROCLIMATIC TRENDS

MOTIVATION

- Closest thing available to ground truth about the nature of hydroclimatic changes
- Key component of any attempt to come to grips with the implications of climate change
- Complement to modeling-based, future-looking simulation studies commissioned by Hydrology & Technical Series; benchmark against which climate projections can be assessed

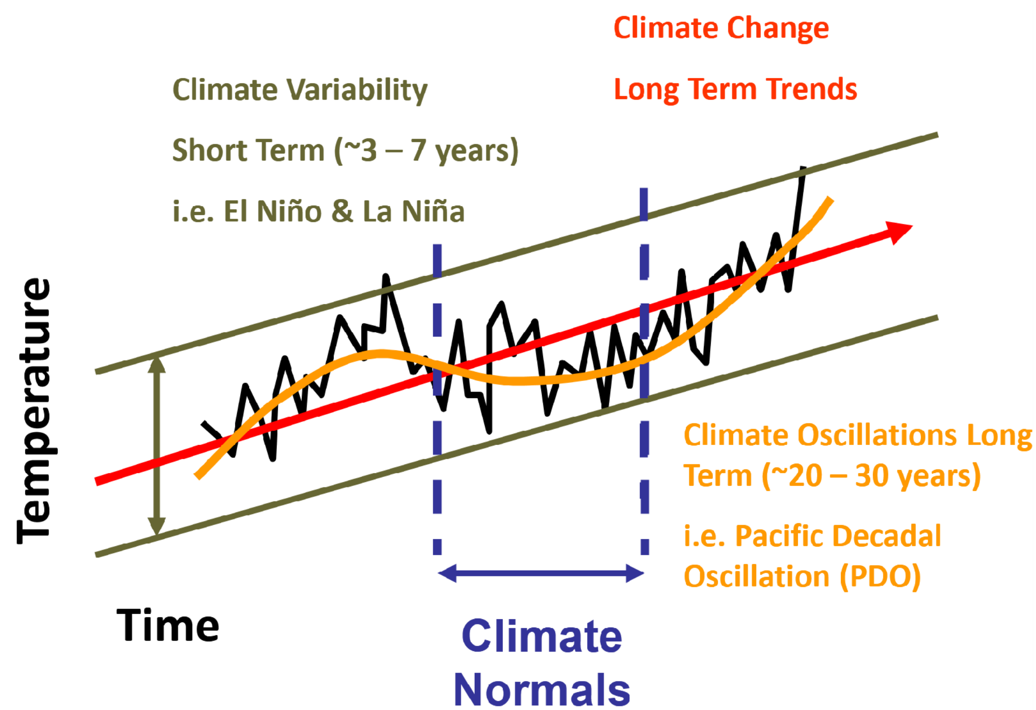
SOME IMPORTANT CONSIDERATIONS

- Trend results are very much dependent on the period analyzed
- Genuine structural trends can be subtle, yet spurious chance trends can appear powerful
- Direct observational records are often short for the purpose of climate impact analysis
- Hydroclimatic datasets can be subject to substantial measurement errors, such as those arising from station moves, local land use changes, shifts in rating curves, or issues around the FLOCAL inflow estimation process

EMPIRICAL ANALYSIS OF HYDROCLIMATIC TRENDS

MORE IMPORTANT CONSIDERATIONS

- Pragmatically relevant philosophical ambiguities around trend analysis – for instance, what constitutes a monotonic trend over one timescale of observation can be part of an oscillation over a longer timescale of observation
- Over longer (e.g., geologic) timescales there are few if any truly permanent, monotonic trends in geophysical series
- Superposition of cyclic and continuous trends (from natural dynamic processes) onto non-cyclic patterns (expected of man's activities)
- Long-memory processes like the Hurst effect and fractal dynamics seem to raise questions about the fundamental nature of hydroclimatic trends and the concept of stationarity

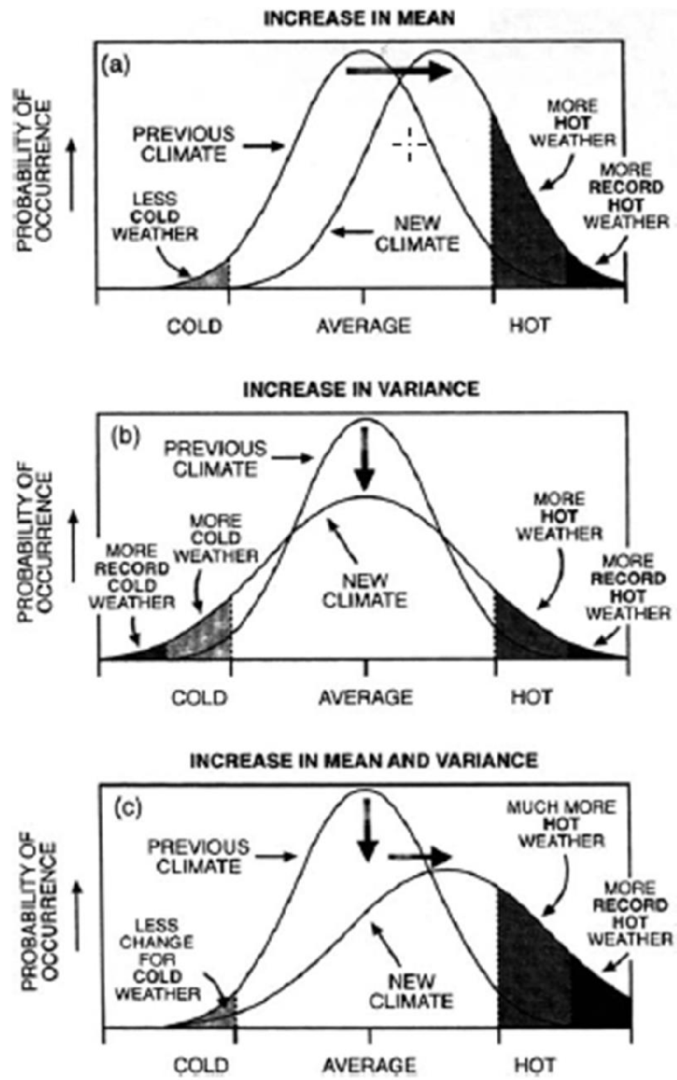


Source: PCIC 2010

EMPIRICAL ANALYSIS OF HYDROCLIMATIC TRENDS

STATISTICS OF INTEREST

- First-order instationarity: presence, direction, magnitude and nature (gradual, abrupt, progressive, linear, non-linear) of long-term changes in average hydroclimatic conditions
- Second-order instationarity: changes in variability, such as year-to-year variability



From M. JAMES SALINGER. 2005. CLIMATE VARIABILITY AND CHANGE: PAST, PRESENT AND FUTURE – AN OVERVIEW, Climatic Change (2005) 70: 9–29

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EMPIRICAL ANALYSIS OF HYDROCLIMATIC TRENDS

TEMPERATURE TRENDS OVER THE 1900-2004 PERIOD *

- Warming across all of BC
  - Particularly minimum temperatures, in winter-spring and in northern BC
  - "It got less cold"
  - Exception: decreases in maximum daily temperatures in summer-fall

PRECIPITATION TRENDS OVER THE 1900-2004 PERIOD *

- Generally increasing precipitation, but spatially variable
  - Particularly in winter-spring, and in northern BC
  - Decreases or no trends in southwestern BC
  - Results impacted by dry 1930s; e.g., decreases over the 1950-2004 period in interior BC

APRIL 1 SNOW WATER EQUIVALENT TRENDS OVER THE 1951-2007 PERIOD **

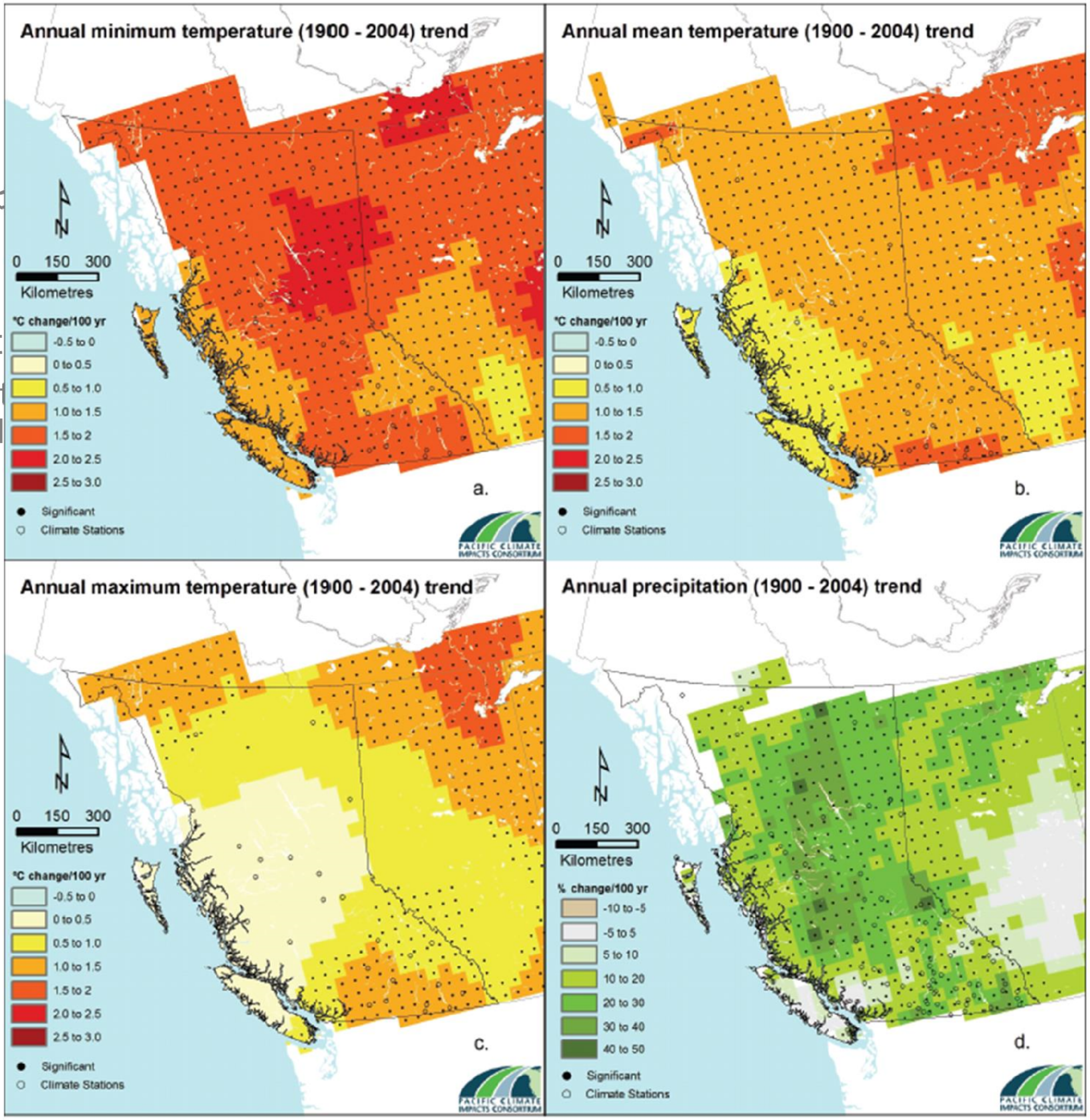
- Decreases over the 1951-2007 period, but increases and decreases over the 1978-2007 period
- Changes are elevation dependent; but data represent mostly 1200-1700 m a.s.l.
- Only April 1 data analyzed, assuming that it represents maximum annual snow water supply; however, changes in timing of snow accumulation and ablation are not considered

* PCIC 2007, based on CANGRID 1900-2004 data
** PCIC 2007, based on in-situ 1951-2007 data

HISTORICAL HYDROC

Annual trends in **mean temp**
British Columbia.

- Results are based on 1900 t
- Black solid circles indicate st confidence level). Open circl Historical Canadian Climate
- Source data: CANGRID (50
- Source: PCIC 2007



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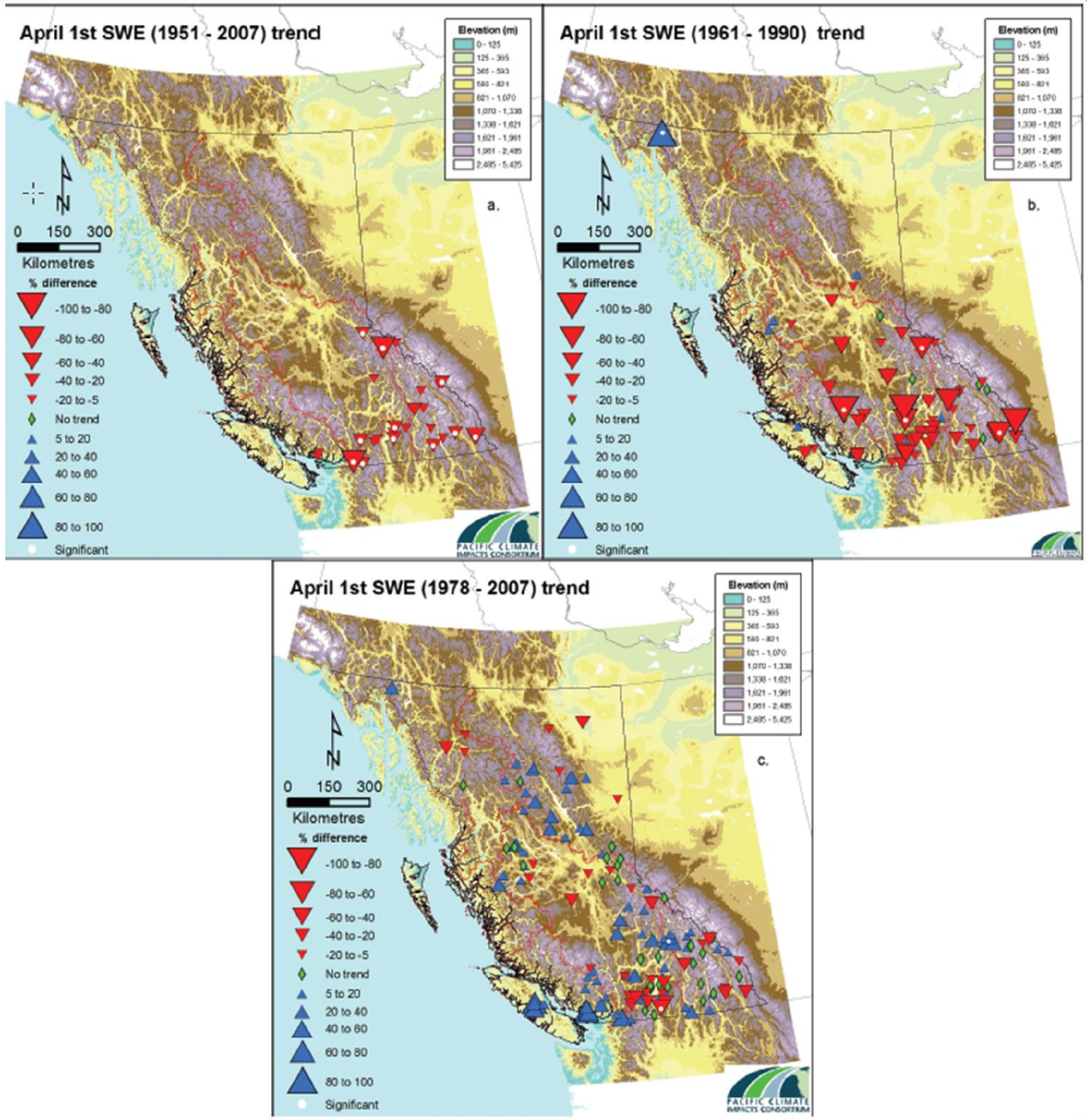
HISTORICAL HYDROCLIMATIC TRENDS

Trends in **April 1 SWE** for British Columbia.

Source data: BC RFC

Source: PCIC 2007



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HISTORICAL HYDROCLIMATIC TRENDS

GLACIER VOLUME TRENDS

- Major glacier recession in the 20th century
- The annual volume loss in BC over the 1985-1999 period is 22.48 ± 5.53 km^3/a*
- Coastal ranges lost the largest fraction of ice

* Schiefer, E., Menounos, B.,, and Wheate R., 2007. Recent volume loss of British Columbia glaciers, Canada. Geophysical Research Letters 34, L16503, doi:10.1029/2007GL030780.

HISTORICAL HYDROCLIMATIC TRENDS

INFLOW TRENDS OVER THE 1984-2007 PERIOD*

- Most of the historical trends are quite subtle
- No evidence for declining annual total water supply - some evidence for a modest historical increase
- Clear evidence for some changes in the seasonality of inflows
  - Fall-winter inflows have shown an increase at all almost all locations considered
  - Weaker evidence for a possible modest decline in late-summer flows for those basins driven primarily by melt of glacial ice and/or seasonal snowpack
- Overall conclusions with respect to long-term trends in water supply were found to be largely insensitive to methodological (data selection, processing and analysis) choices
- No evidence was found for historical changes in the severity of year-to-year fluctuations in annual reservoir inflow volumes. This result implies that the reliability of annual water supply has not changed appreciably.

* BC Hydro 2010

HISTORICAL HYDROCLIMATIC TRENDS

BC HYDO RESERVOIR INFLOW TRENDS

REGION	PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	yr
south coastal	SCA	0.7	1.9	**2.1**	1.9	-1.3	-0.1	0.3	0.8	1.1	0.8	0.0	0.2	0.7
	CMX	0.4	0.7	**0.9**	0.9	-0.7	0.1	0.4	0.4	0.4	0.3	0.0	0.1	**0.3**
	ASH	0.2	0.1	0.4	0.4	-0.6	-0.1	-0.1	0.0	0.0	0.2	0.1	0.1	0.0
	JOR	0.2	0.0	0.5	0.6	-0.3	0.4	-0.1	-0.2	0.0	0.0	0.0	0.1	0.1
	ALU	0.3	-0.1	**0.7**	0.4	-0.3	0.5	-0.1	-0.2	0.1	0.2	0.1	0.1	0.2
	CQD	0.2	-0.1	**0.7**	0.5	-0.3	0.4	0.0	-0.1	0.2	0.2	0.1	0.1	0.2
	SFL	1.0	0.0	**3.5**	2.4	-1.6	1.8	-0.1	-0.2	0.5	0.8	0.4	0.2	0.7
	WAH	0.1	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	COM	0.4	0.4	**0.9**	0.7	-0.5	0.2	0.1	-0.1	0.3	0.7	0.0	0.2	0.3
	CMS	0.2	0.4	**0.7**	0.7	-0.3	-0.1	0.0	-0.3	-0.2	-0.1	-0.5	-0.1	0.0
Bridge	BRR	0.0	0.1	0.3	0.1	-0.1	-0.1	0.0	0.1	0.9	0.9	-0.3	0.2	0.2
	LAJ	-0.3	0.0	0.1	0.1	0.1	0.0	0.1	0.3	0.7	0.7	-0.7	-0.4	0.1
Columbia	MCD	3.7	1.3	**1.8**	**1.7**	0.9	0.9	0.7	-0.1	1.1	7.3	-5.1	0.0	1.2
	REV	1.5	0.0	-0.1	0.7	-0.2	-0.1	0.1	0.9	1.7	3.4	-0.9	0.2	0.6
	ARD	2.1	0.3	1.5	1.7	0.9	1.4	-0.4	2.0	0.5	0.0	-2.0	0.1	0.7
	WGS	0.1	0.0	0.0	0.1	**0.1**	0.1	0.1	0.2	0.2	0.0	0.0	0.0	0.1
	SGR	0.5	0.2	0.2	**0.3**	0.2	0.1	-0.1	0.1	0.5	-0.3	-0.3	0.0	0.1
Kootenays	DDM	1.2	0.3	0.0	0.2	0.1	0.1	0.1	0.9	0.2	1.5	-0.6	0.9	0.4
	KLK	1.7	-0.8	2.1	3.0	1.1	3.3	-1.8	4.1	3.5	1.4	0.1	0.5	1.5
Peace	GMS	-1.6	0.5	0.2	-0.4	2.0	0.4	2.4	-3.1	22.2	-2.3	1.4	1.8	2.0
combined usable inflow	n/a	9.6	7.1	**14.6**	**14.2**	1.1	6.2	4.0	-0.8	39.7	21.2	-14.6	1.7	8.7

Trends presented as linear slopes in $m^3/s/yr$ for mean volumetric flow rates, or GWh/yr for combined usable inflow, over the 1984-2007 period. Blue and red shading indicate positive and negative water resource trends, respectively; slope values with a magnitude equal to zero within one decimal place are left uncoloured. Trends with signal-to-noise ratios 0.1 or greater are outlined by a box; those with S:N $\geq$ 0.20 are additionally illustrated in bold font.

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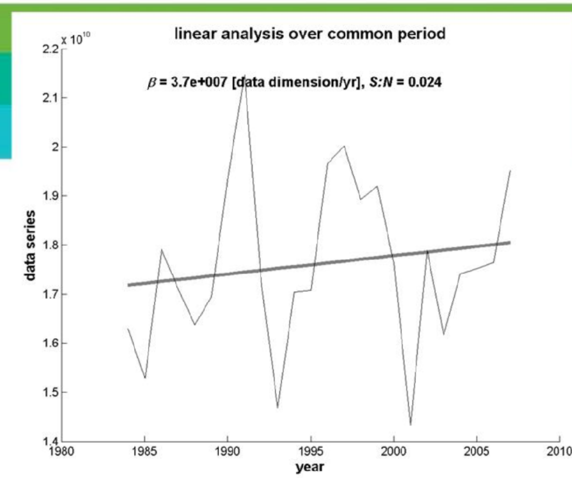
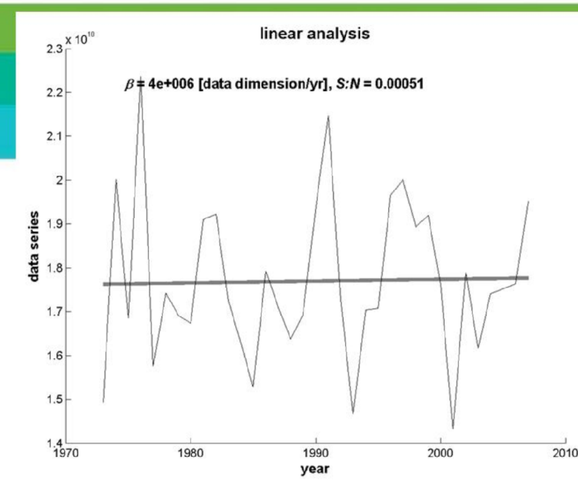
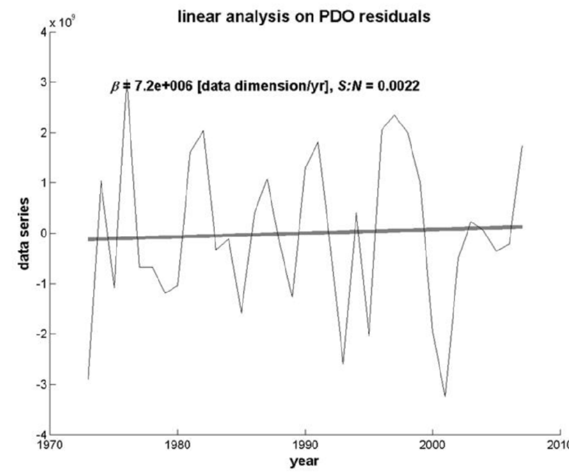
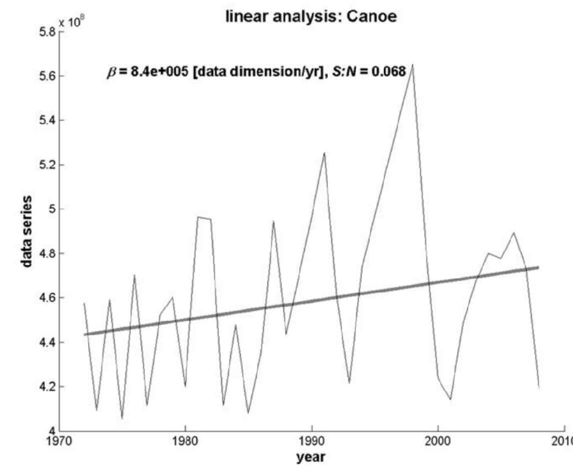
MICA INFLOW TRENDS

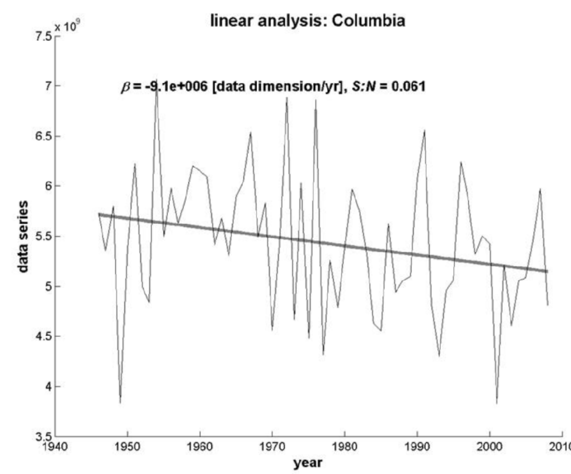
Results of primary and auxiliary analyses for Mica annual inflow volumes in m^3

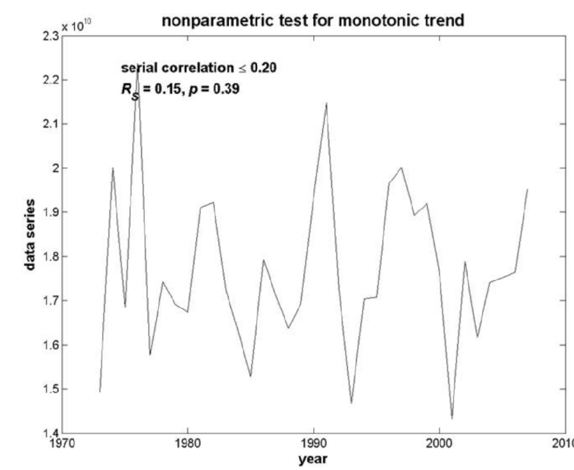












BC hydro
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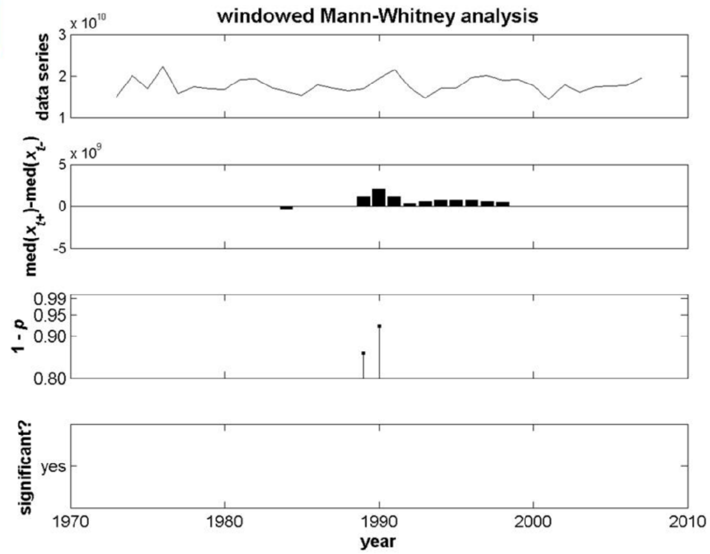
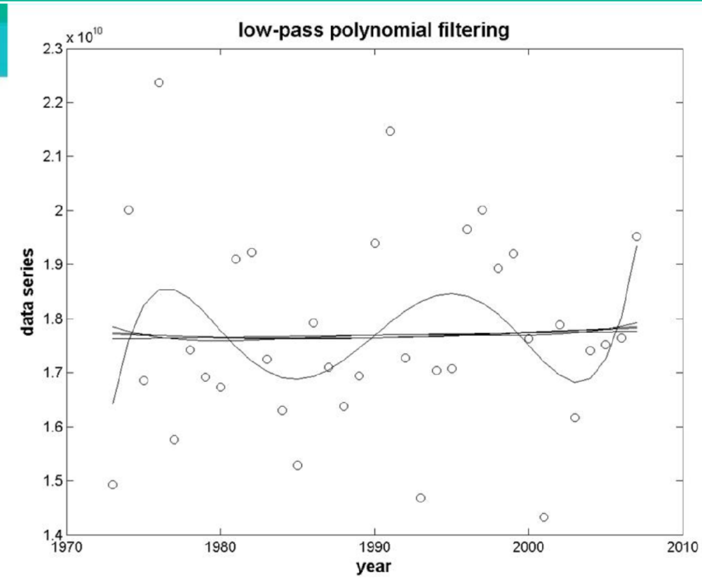
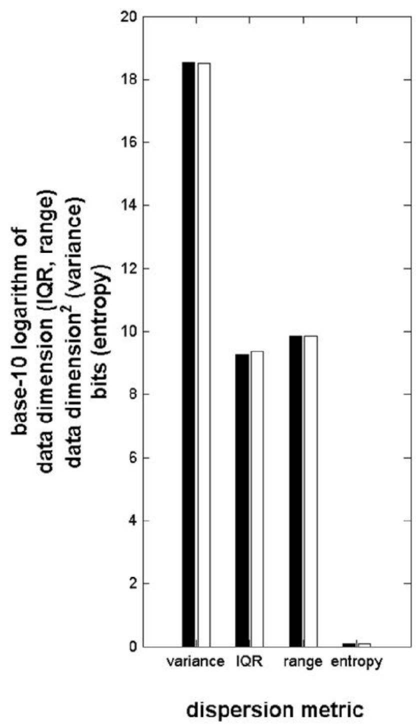
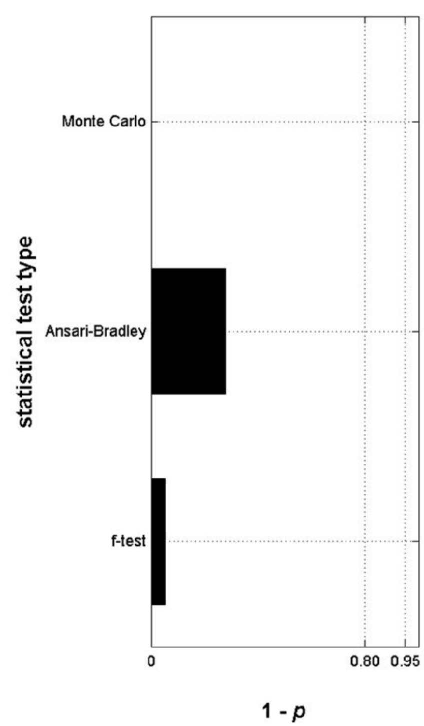
MICA INFLOW TRENDS

Results of primary and auxiliary analyses for Mica annual inflow volumes in m^3









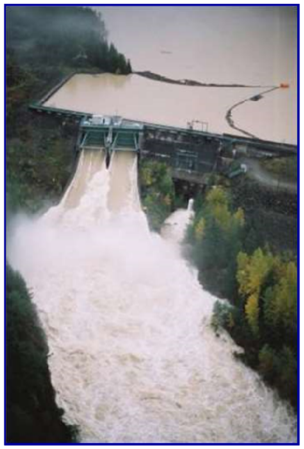
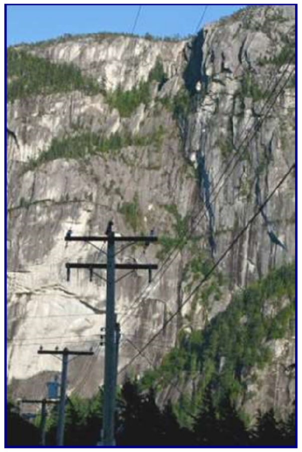
SUMMARY

- Analysis of historic hydroclimatic trends complements modeling-based, future-looking simulation studies commissioned by Hydrology & Technical Series; benchmark against which climate projections can be assessed
- Temperatures
  - General warming across all of British Columbia
- Precipitation
  - Generally increasing precipitation, but the signal is spatially variable (for example decreases or no trends in southwestern BC)
- Seasonal maximum snowpack
  - April 1 SWE decreases over the 1951-2007 period, but increases and decreases reported over the 1978-2007 period, and primarily for the 1200-1700 m elevation range
- Glaciers
  - Negative trends of glacier volume in BC over the 1985-1999 period
- Inflow
  - Most of the historical trends are quite subtle
  - No evidence for declining annual total water supply - some evidence for a modest historical increase
  - Clear evidence for some changes in the seasonality of inflows
    - Fall-winter inflows have shown an increase at all almost all locations considered
    - Weaker evidence for a possible modest decline in late-summer flows for those basins driven primarily by melt of glacial ice and/or seasonal snowpack
  - No evidence was found for historical changes in the severity of year-to-year fluctuations in annual reservoir inflow volumes.

THANKS FOR LISTENING

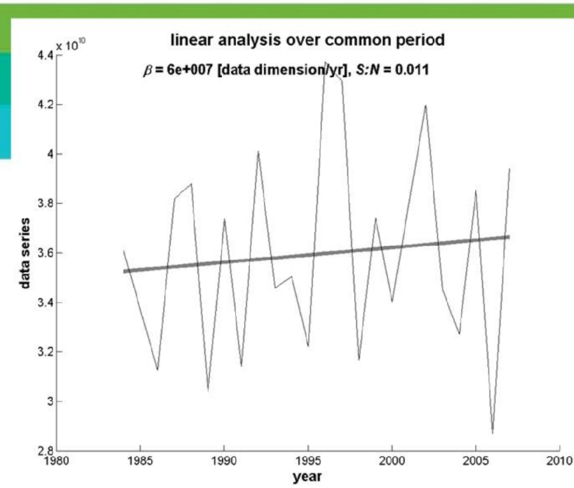


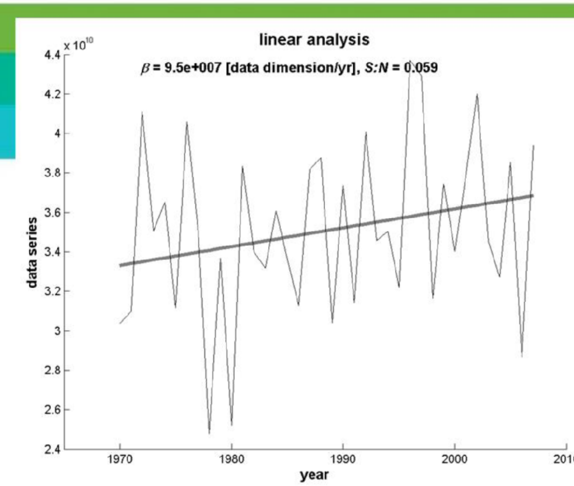


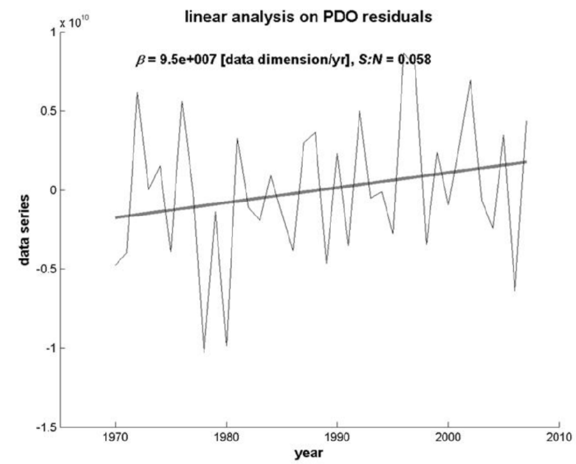



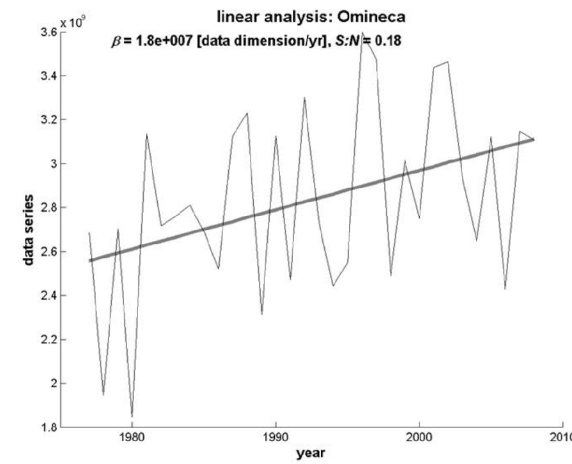
WILLISTON INFLOW TRENDS

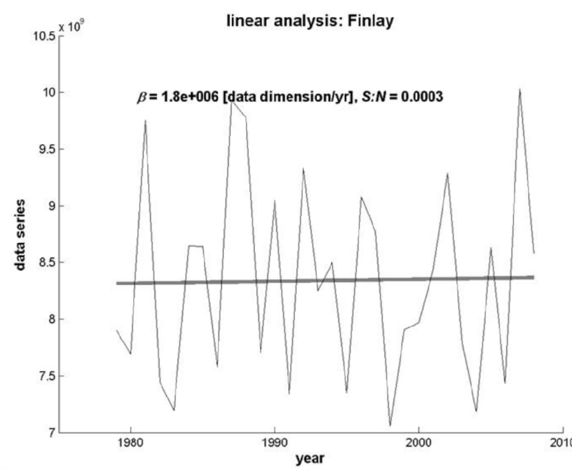
Results of primary and auxiliary analyses for Williston annual inflow volumes in m^3

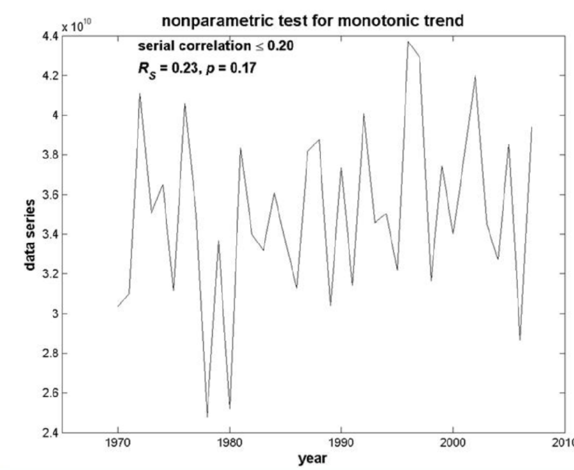












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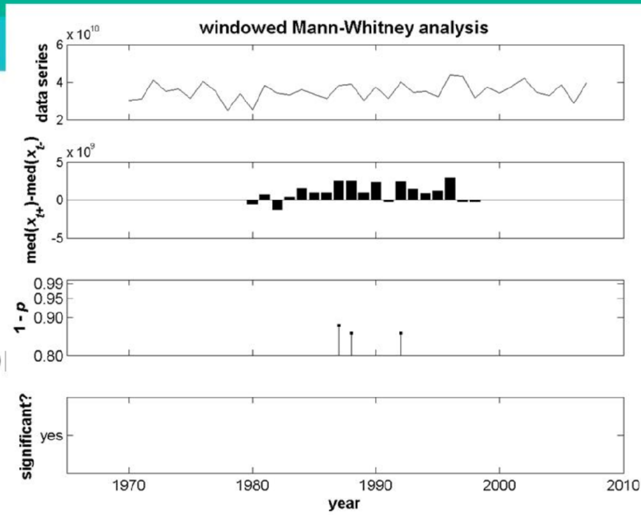
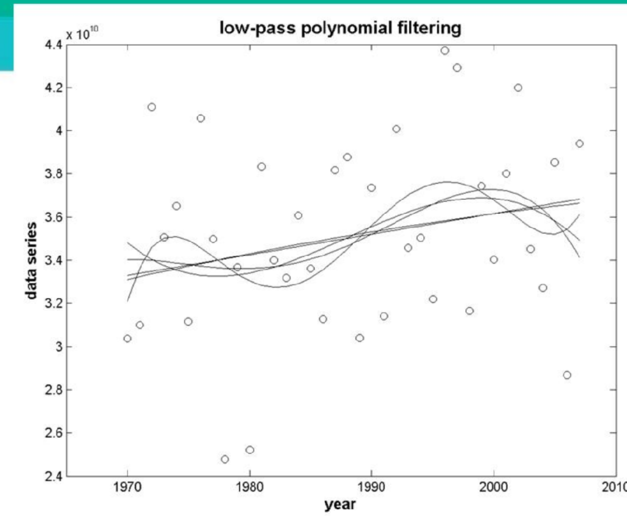
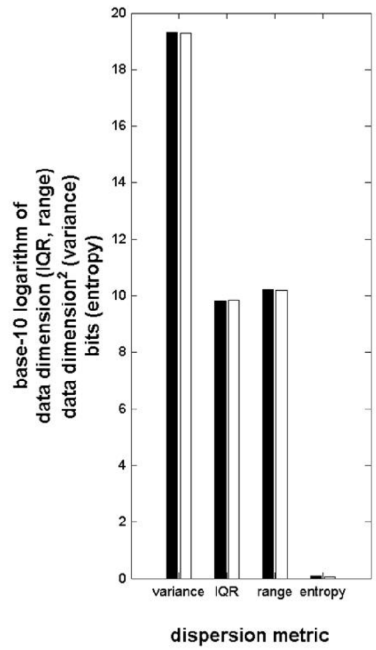
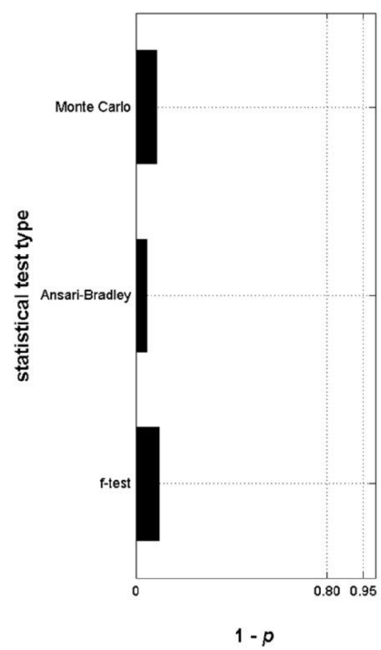
WILLISTON INFLOW TRENDS

Results of primary and auxiliary analyses for Willisto annual inflow volumes in m^3



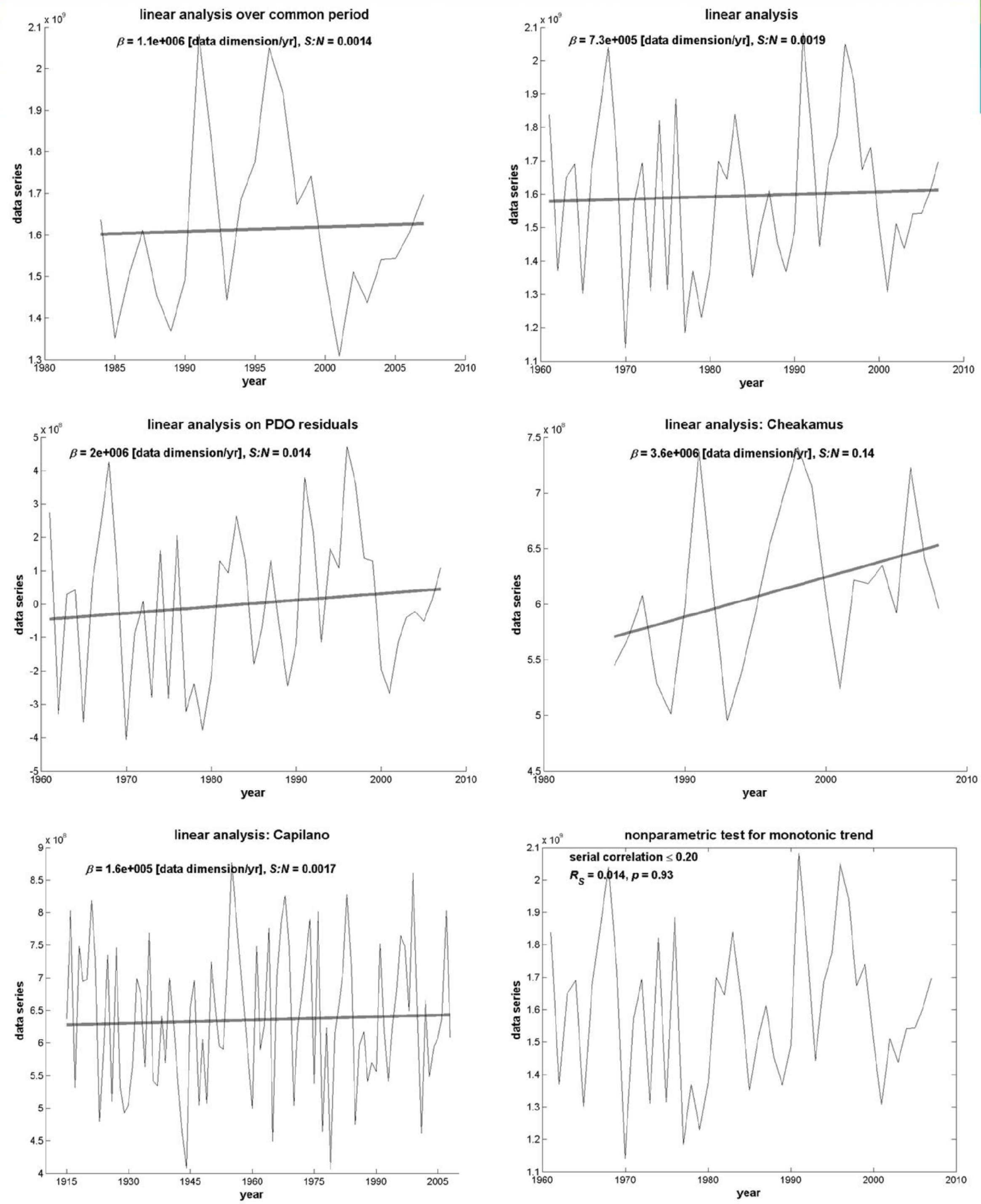






CHEAKAMUS INFLOW TRENDS

Results of primary and auxiliary analyses for Cheakamus annual inflow volumes in m^3



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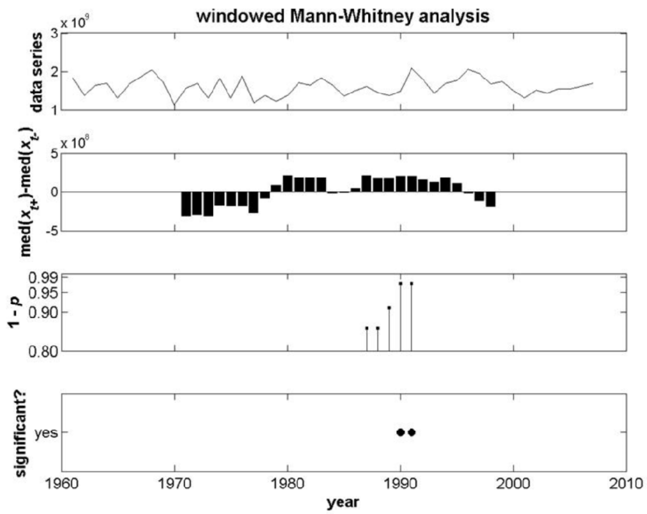
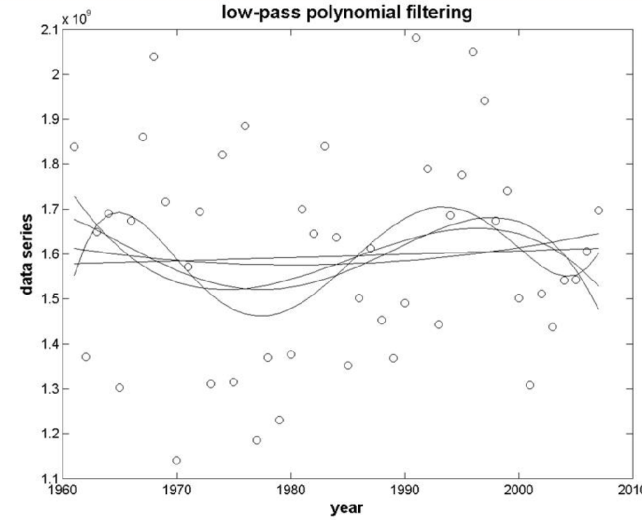
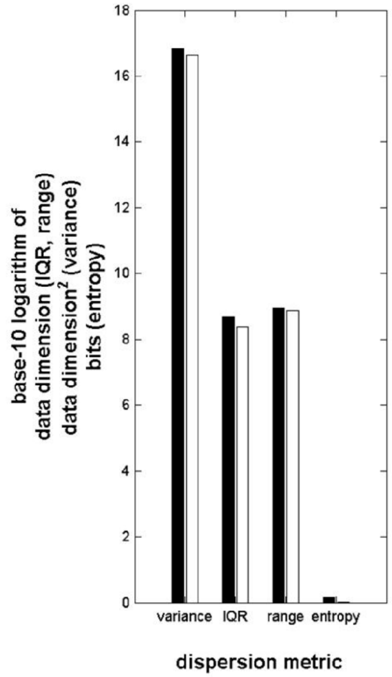
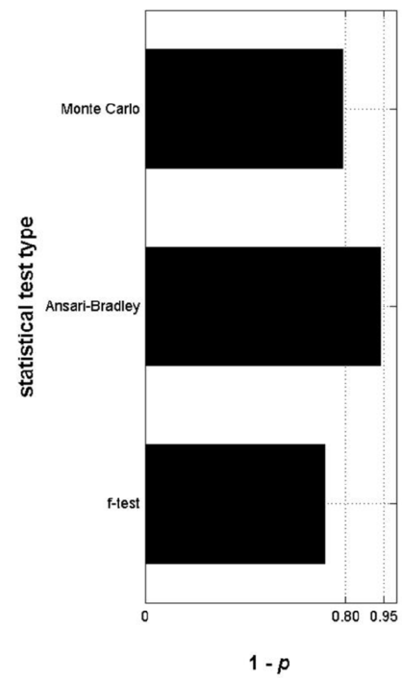
CHEAKAMUS INFLOW TRENDS

Results of primary and auxiliary analyses for Chea annual inflow volumes in m









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CLIMATE CHANGE IMPACT STUDIES AT BC HYDRO

Portland, Oregon, October 2009

Sean W Fleming, PhD, PPhys, ACM, PGeo
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H&TS ROLE IN CLIMATE CHANGE STUDIES

WHAT CORE ORGANIZATIONAL FUNCTIONS DO WE PERFORM?

- Environmental data collection and management
- Operational weather & reservoir inflow forecasting
- R&D to support improved forecasting

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H&TS ROLE IN CLIMATE CHANGE STUDIES

WHAT CORE ORGANIZATIONAL FUNCTIONS DO WE PERFORM?

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→ **We are also called upon to generate & communicate knowledge/syntheses re: impacts of climate variability & change upon reservoir inflows. Information passed upward (e.g. board of directors) and downward (e.g. planning engineers).**

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WHY DO WE CARE?

CLIMATE CHANGE IMPLICATIONS TO BC HYDRO

Operations

- 90% hydroelectric
- long-term planning
- changes in hydrologic regime/variability/predictability

Financial

- significant financial effect from small difference in reservoir levels

Environmental

- protect fish
- meet water license requirements
- meet long-term environmental goal

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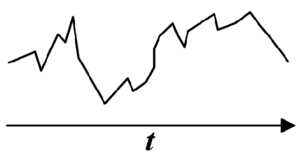
APPROACHES (GENERIC)

HOW DOES ONE STUDY POTENTIAL CLIMATE CHANGE IMPACTS?

- **Restrospective studies**: statistical or time series analysis of historical records



→ *low-pass filtering, nonparametric trend detection, statistical modelling*

- **Future projections**: process modelling to bracket range of potential hydroclimatic trajectories

emissions (social-technical-economic) scenarios → *general circulation models (GCMs)* → *downscaling (statistical or RCM-based)* → *watershed modelling*

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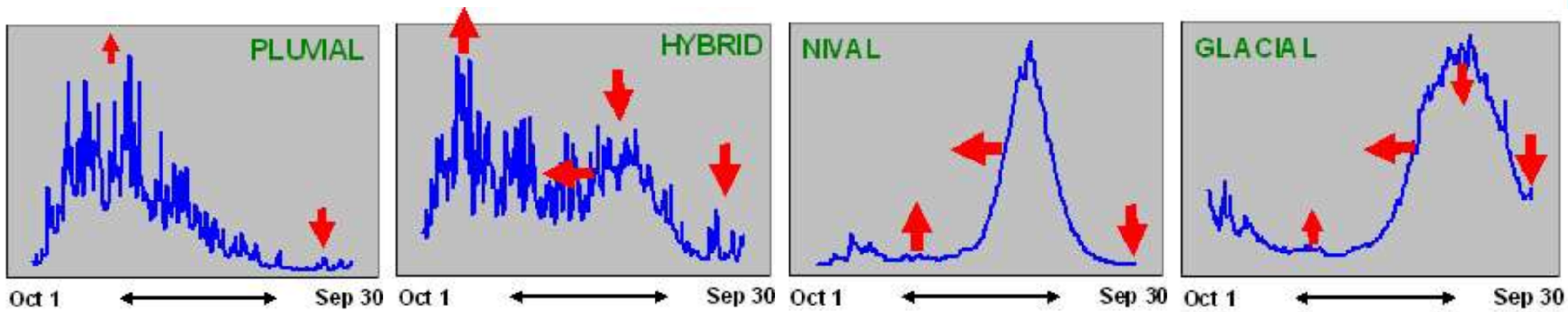
RESULTS (BROAD-BRUSH)

WHAT ARE THE OVERALL DIRECTIONS OF CHANGE IN BC?

- **Temperature**: very likely higher **Precipitation**: maybe higher
- Changes in hydrologic regimes likely – will probably impact mostly on flow timing:



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