EFFECTS OF PROJECTED TWENTY-FIRST CENTURY SEA LEVEL RISE, STORM SURGE, AND RIVER FLOODING ON WATER LEVELS IN PUGET SOUND FLOODPLAINS AND ESTUARIES

MASTER'S THESIS DEFENSE

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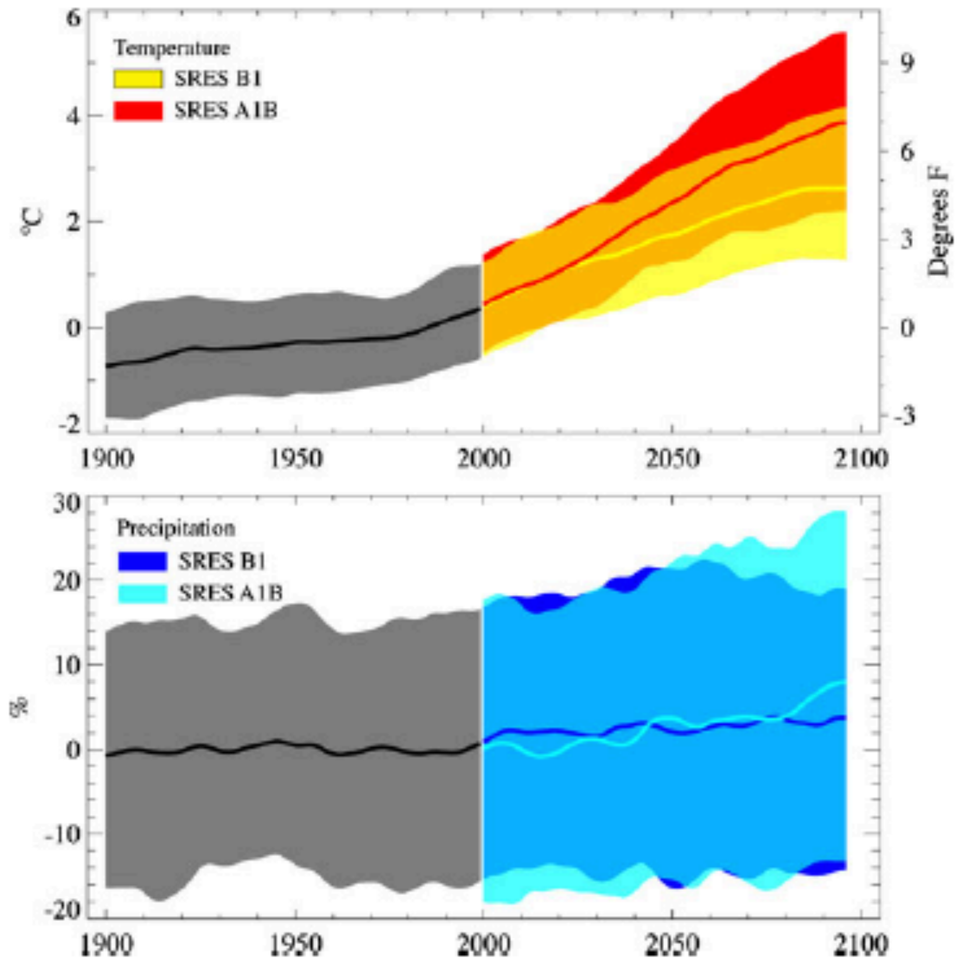
FUTURE CLIMATE CHANGE IN THE PACIFIC NORTHWEST

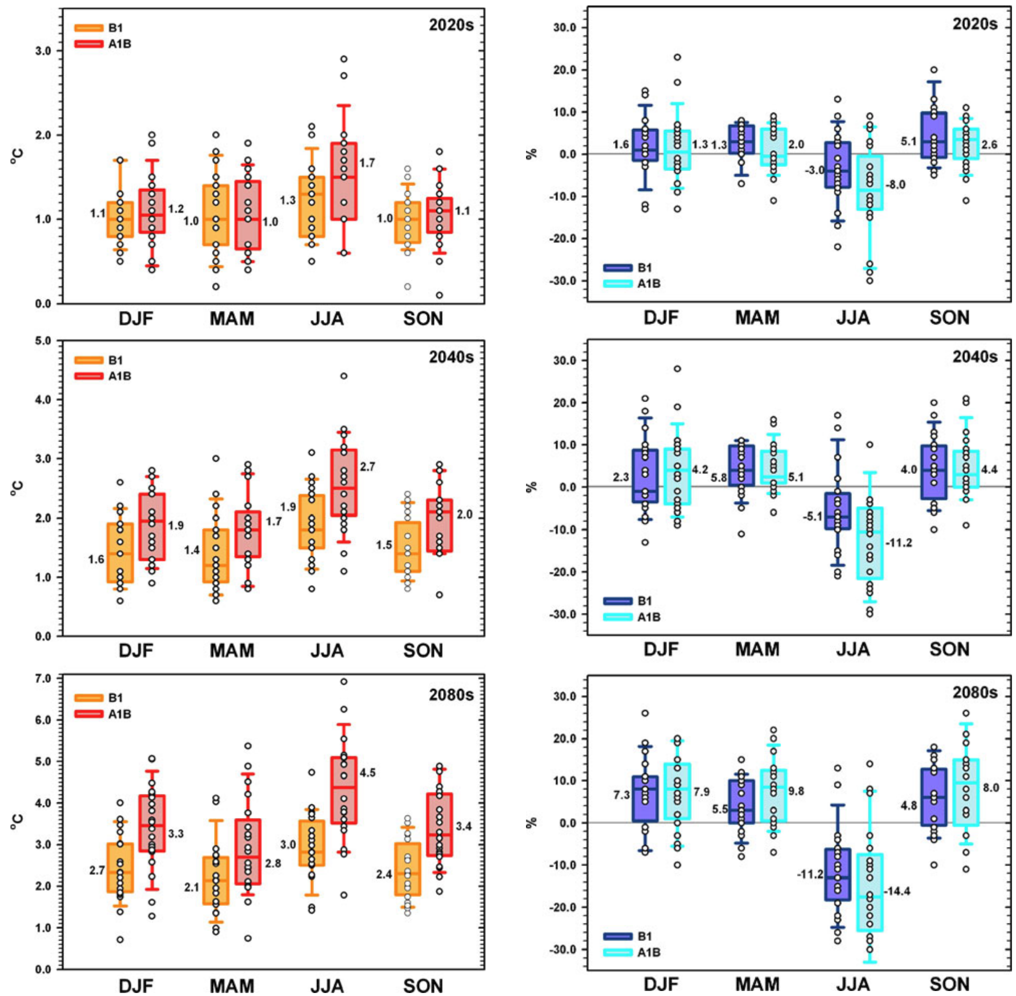
- 20 GCM Climate Projections
  - Temperature
    - 2020s – 1.1°C
    - 2040s – 1.8°C
    - 2080s – 3.0°C
  - Precipitation
    - +1% to +2%



Source: Mote, 2010

FUTURE CLIMATE CHANGE IN THE PACIFIC NORTHWEST

- Seasonal Temperature
  - Largest increases during Summer months
- Seasonal Precipitation
  - Increase in Winter/ Spring/Fall precipitation
  - Decrease in Summer precipitation



Source: Mote, 2010

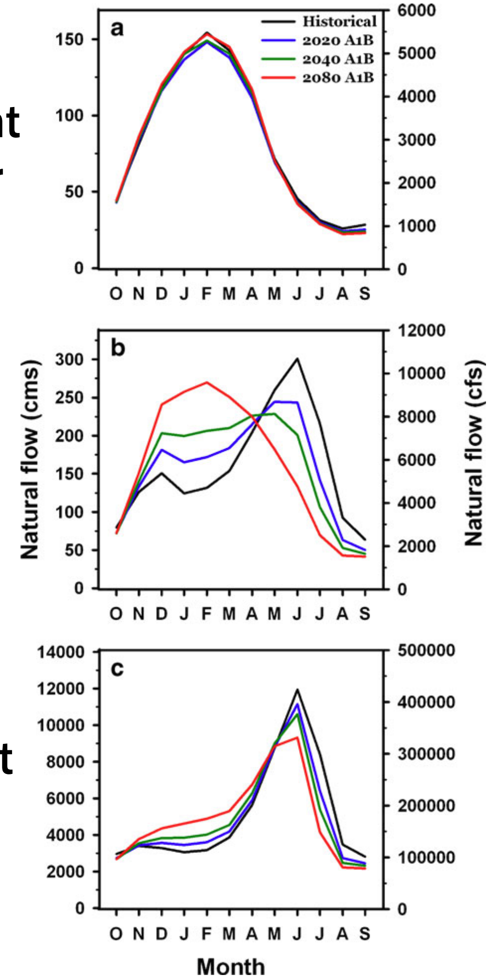
CHANGES IN STREAMFLOW TIMING

- Changes due to warmer temperatures and increased Winter precipitation
  - Rain Dominant Basins: small increases
  - Transient Rain-Snow Basins: shift from spring peak to Fall/ Winter peak
  - Snowmelt Dominant Basins: decrease in Spring/Summer flow

Rain Dominant
Chehalis River

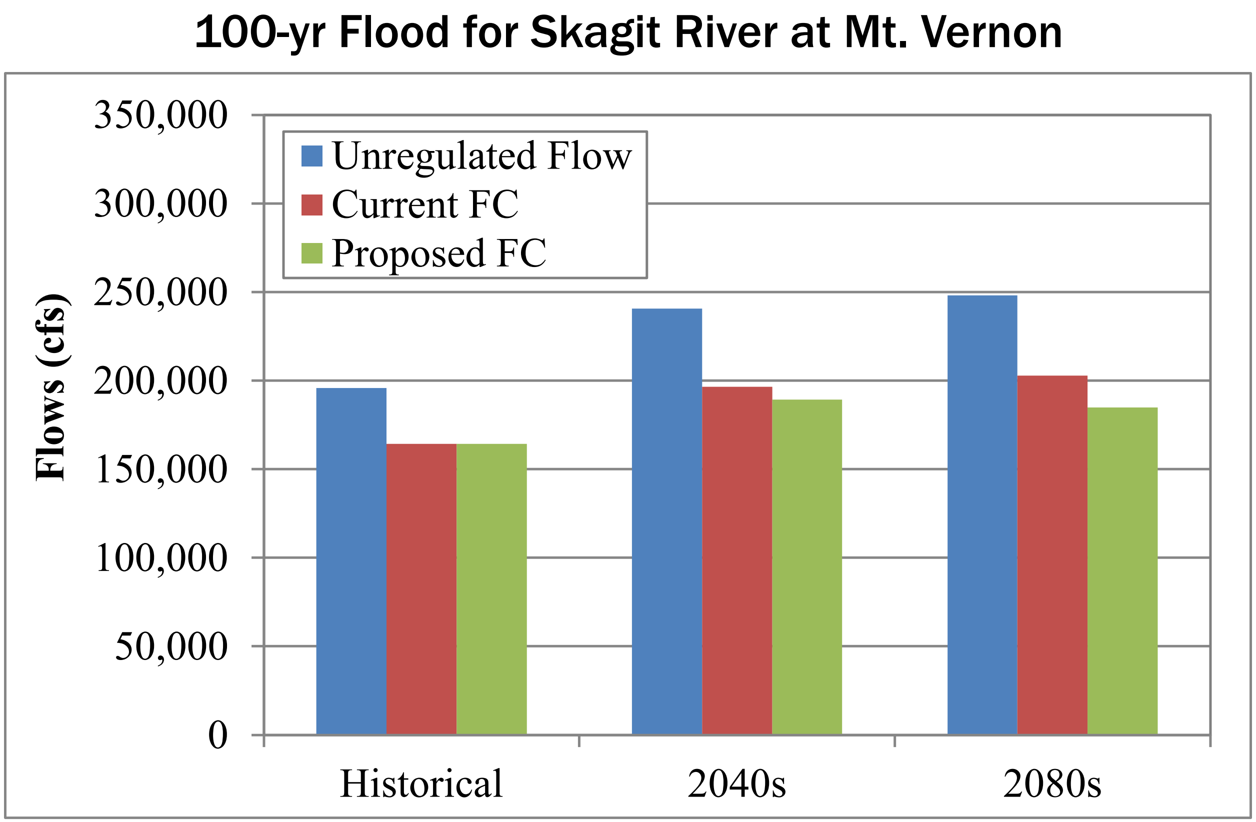
Transient Rain-Snow
Yakima River

Snowmelt Dominant
Columbia River



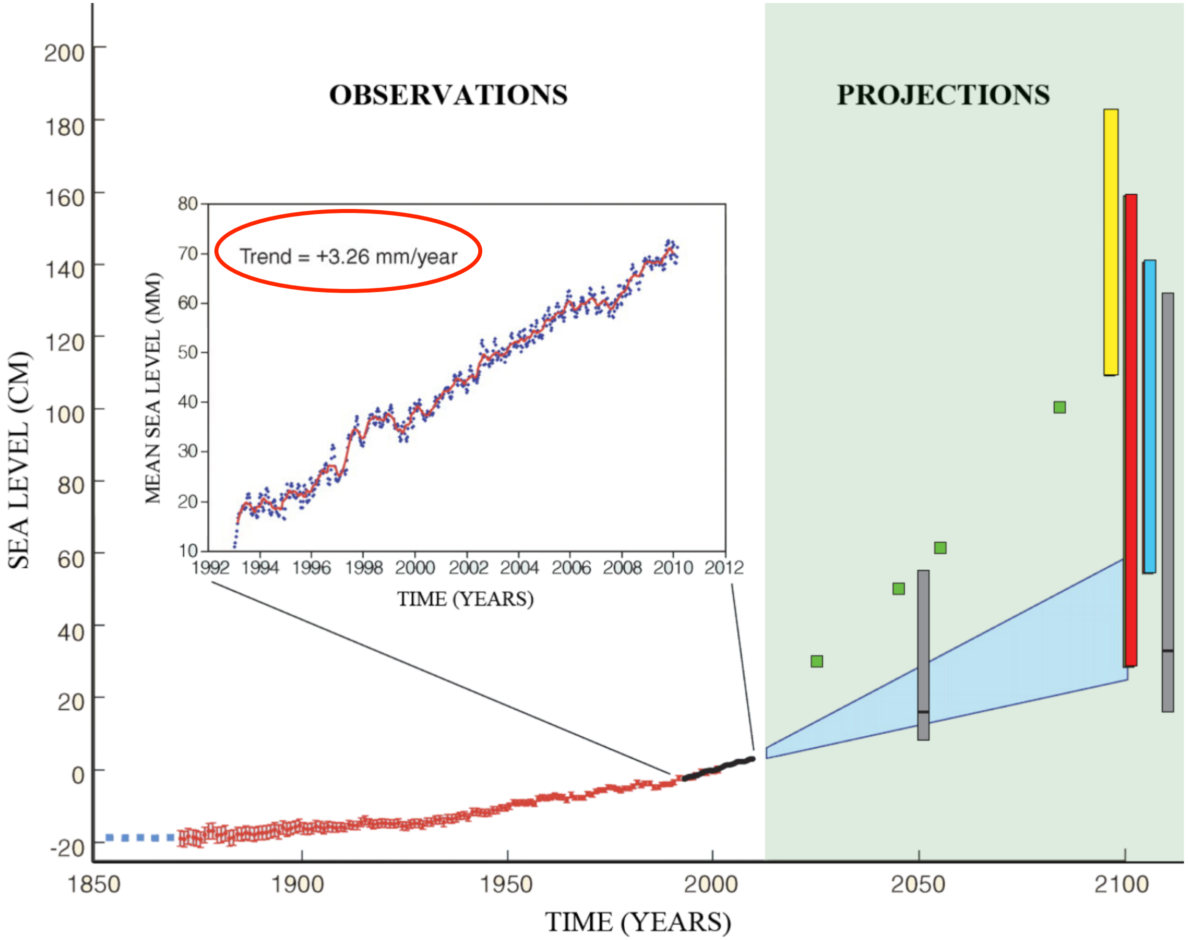
Source: Elsner et at., 2010

REGULATED FLOODING



Source: Lee & Hamlet, 2011

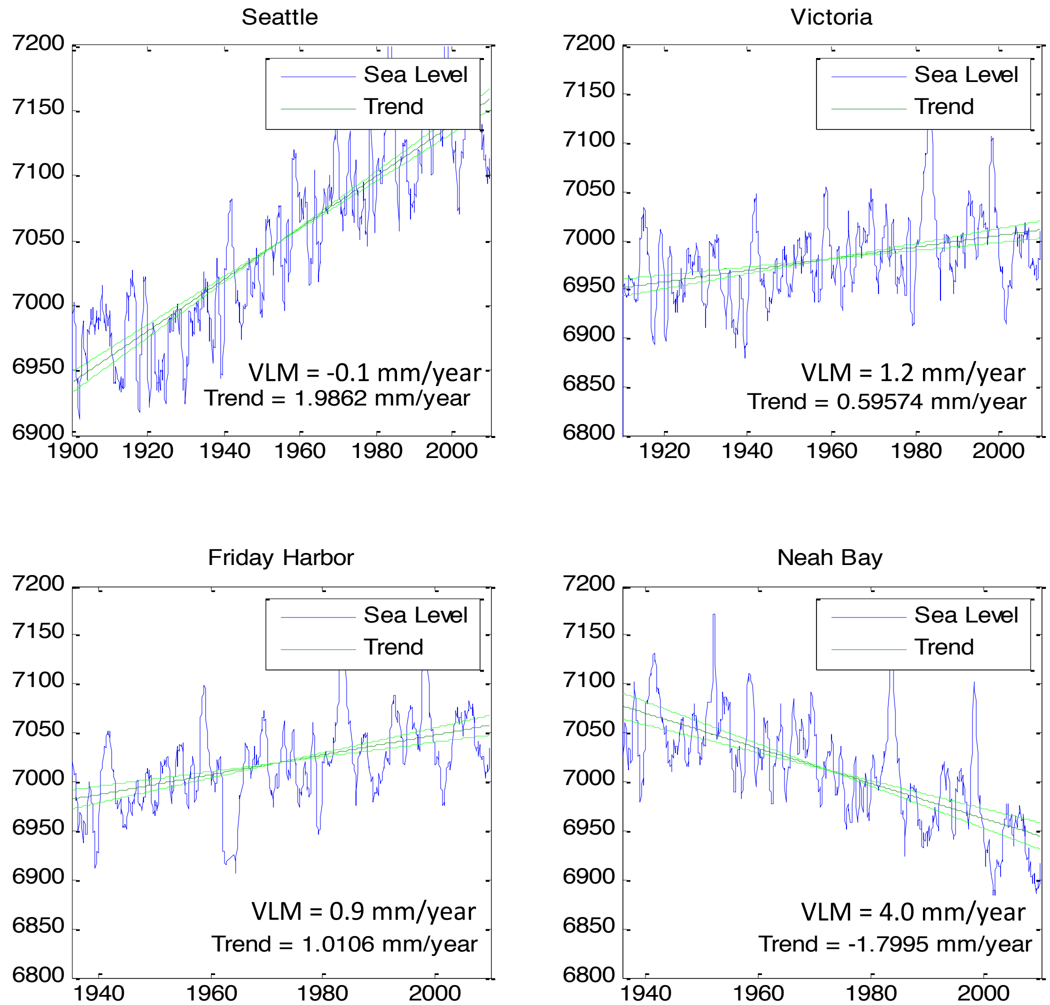
GLOBAL SEA LEVEL RISE



Adapted from Nicholls and Cazenave, 2010

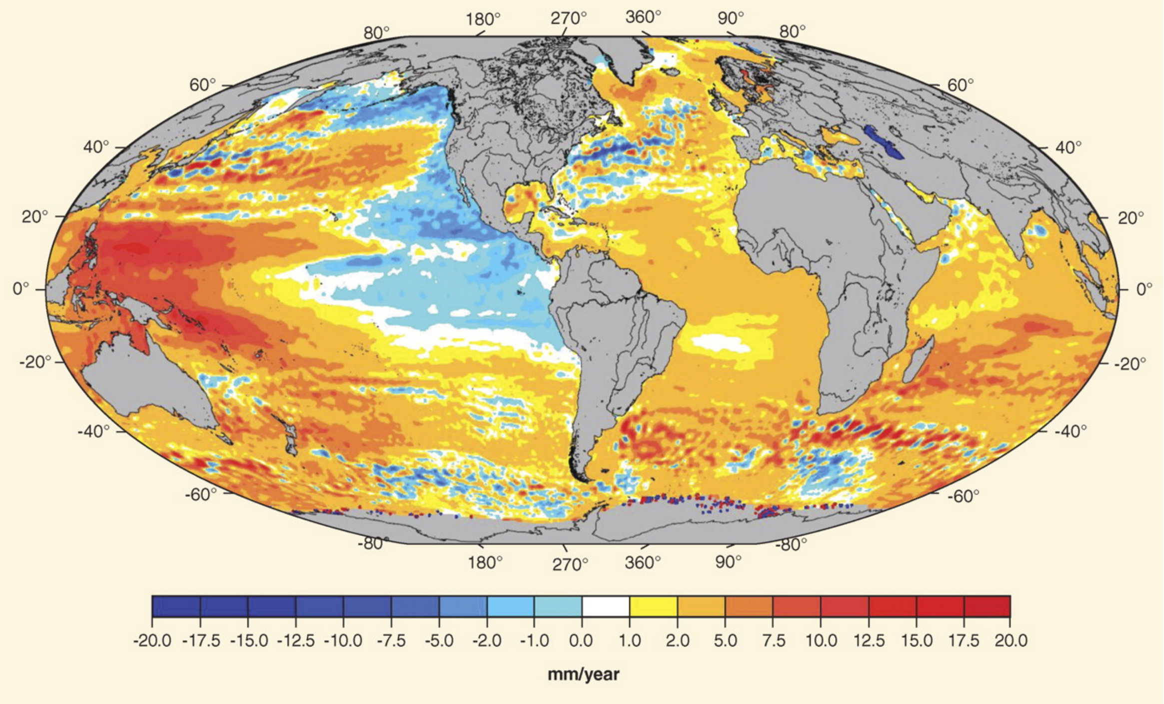
PUGET SOUND SEA LEVEL RISE

- **Puget Sound SLR rate adjusted for vertical land movement is 1.8-2.2 mm/year.**
- **Recent trends in Puget Sound MSL are smaller than 20year global average of 3.26 mm/ year.**



GLOBAL SEA LEVEL RISE

Sea-Level Trends from Satellite Altimetry, 1992 -2009



- Heterogeneous global SLR
- Observed trends in Eastern Pacific sea level are negative over past 20 years
- Likely due to large scale wind patterns
- It is unclear how long this pattern will persist

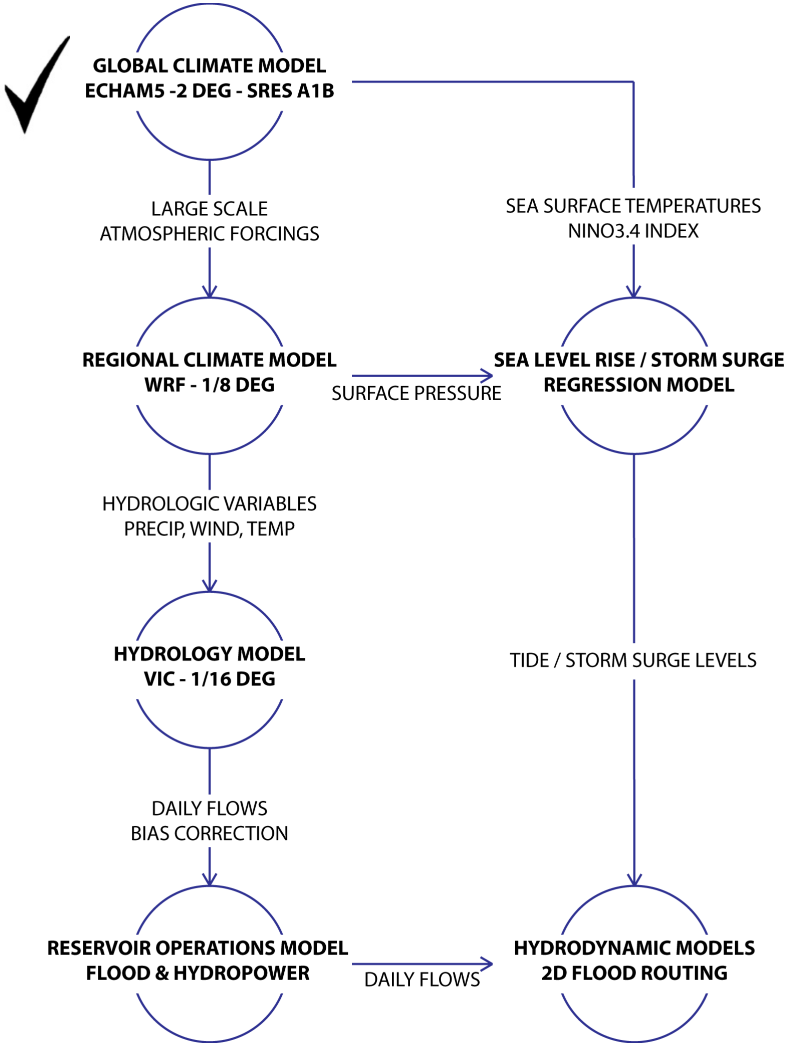
Source: Nicholls and Cazenave, 2010

WHAT WE DON'T KNOW ABOUT CLIMATE CHANGE IMPACTS ON FLOODING

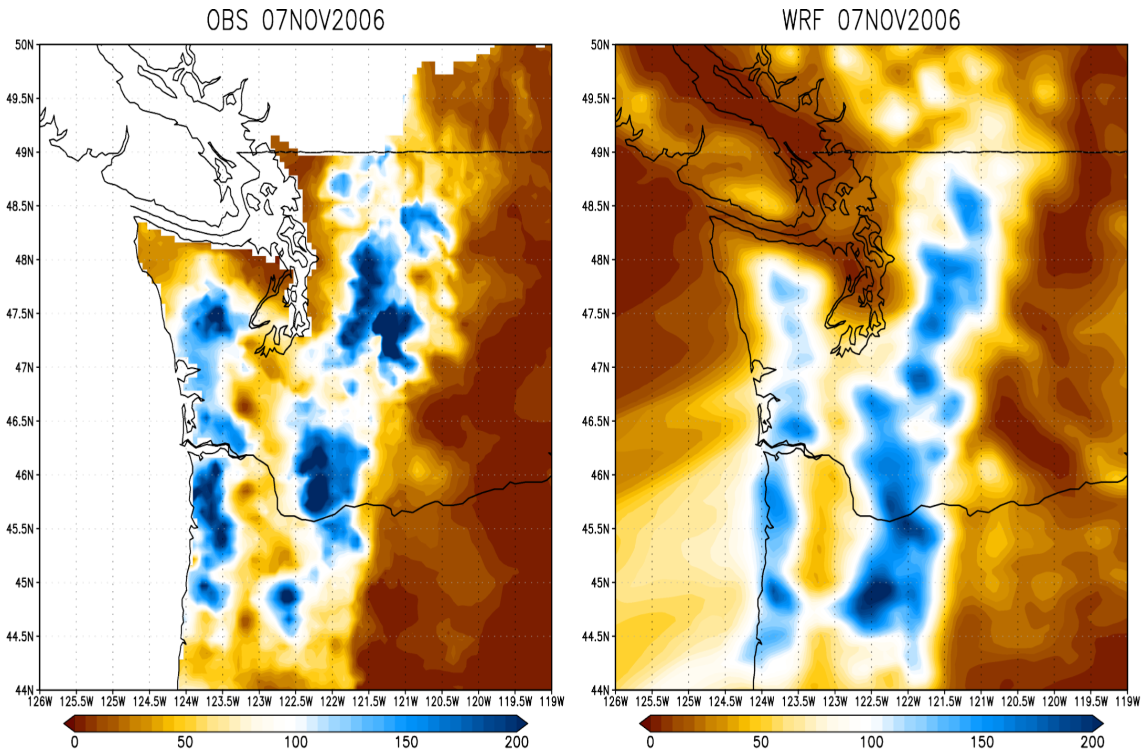
- Combined effects of SLR and Flooding
- Behavior of future storm surge
- Inundation – do the combined effects equate to significant changes in flood inundation and/or depths?
- How do we use all this research for real life floodplain management?

OVERVIEW OF THIS PROJECT

- Assess regulated flooding in the Skagit and Nisqually Rivers
- Develop methods to bring together storm surge, sea level rise and river flooding
- Estimate flood extents/depths in regulated Puget Sound Rivers
- Ultimately, we're trying to get inundation maps from GCM data

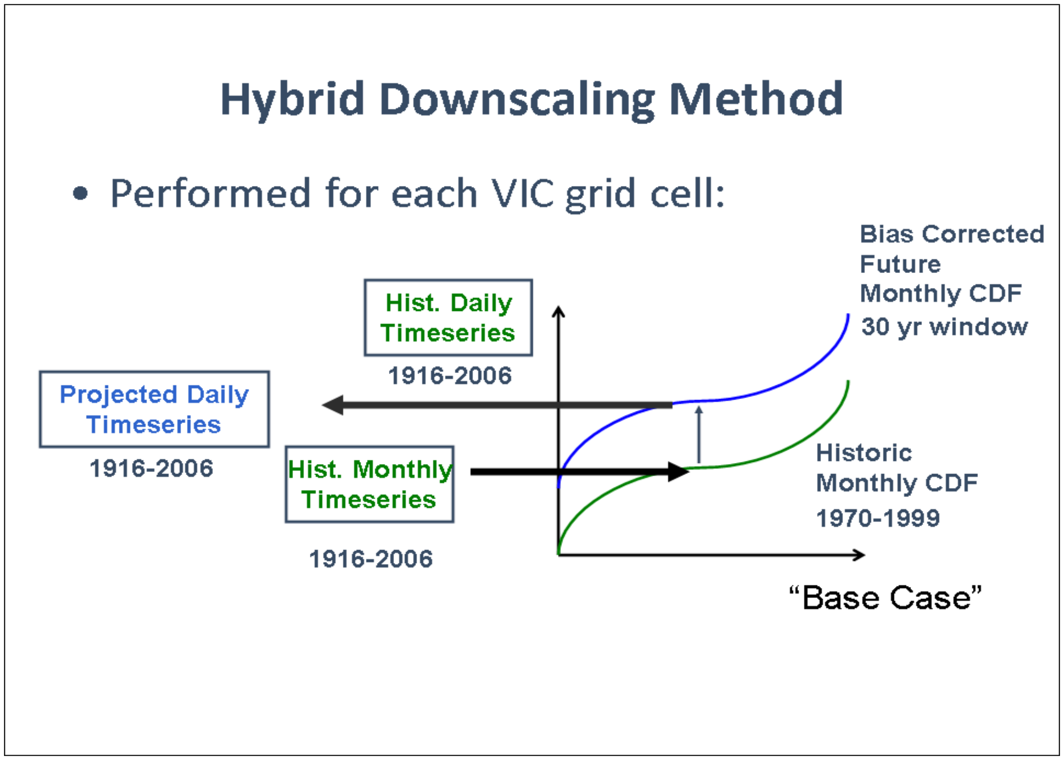


DYNAMIC DOWNSCALING



- WRF provides atmospheric conditions at much higher resolution
- Simulates actual weather prescribed by large scale GCM
- Produces actual storms
- Does not rely on the historical time series
- Three 30-year time periods
  - 1980s, 2020s and 2050s

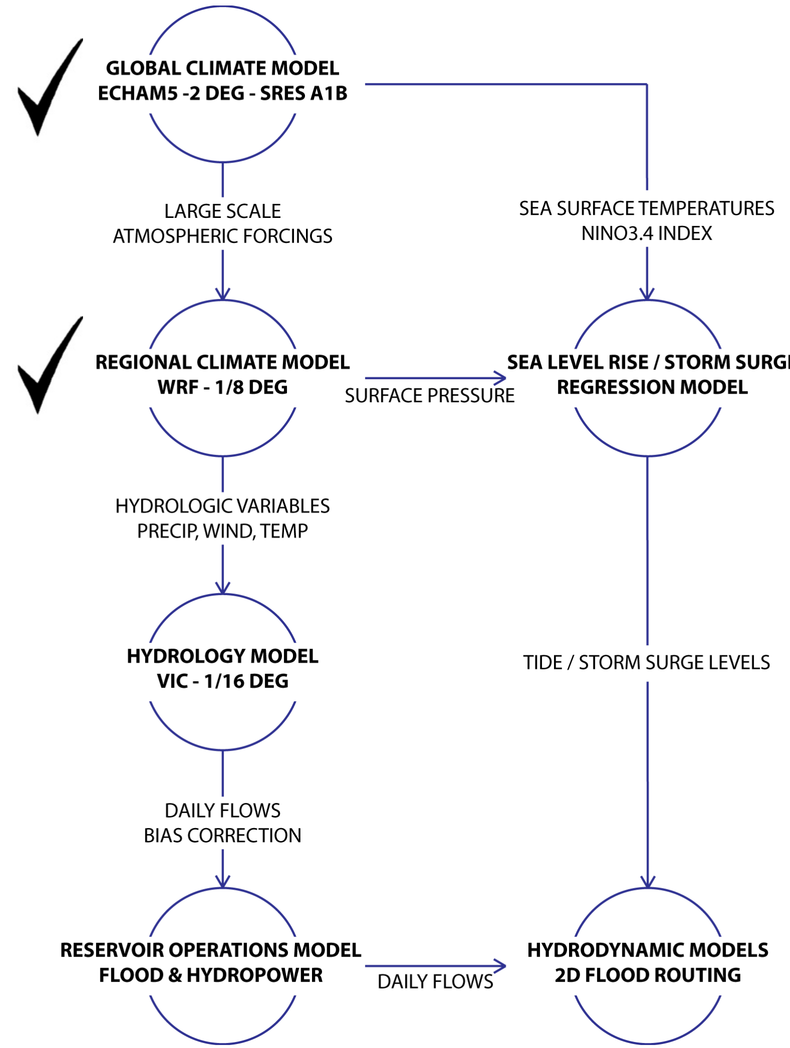
STATISTICAL DOWNSCALING



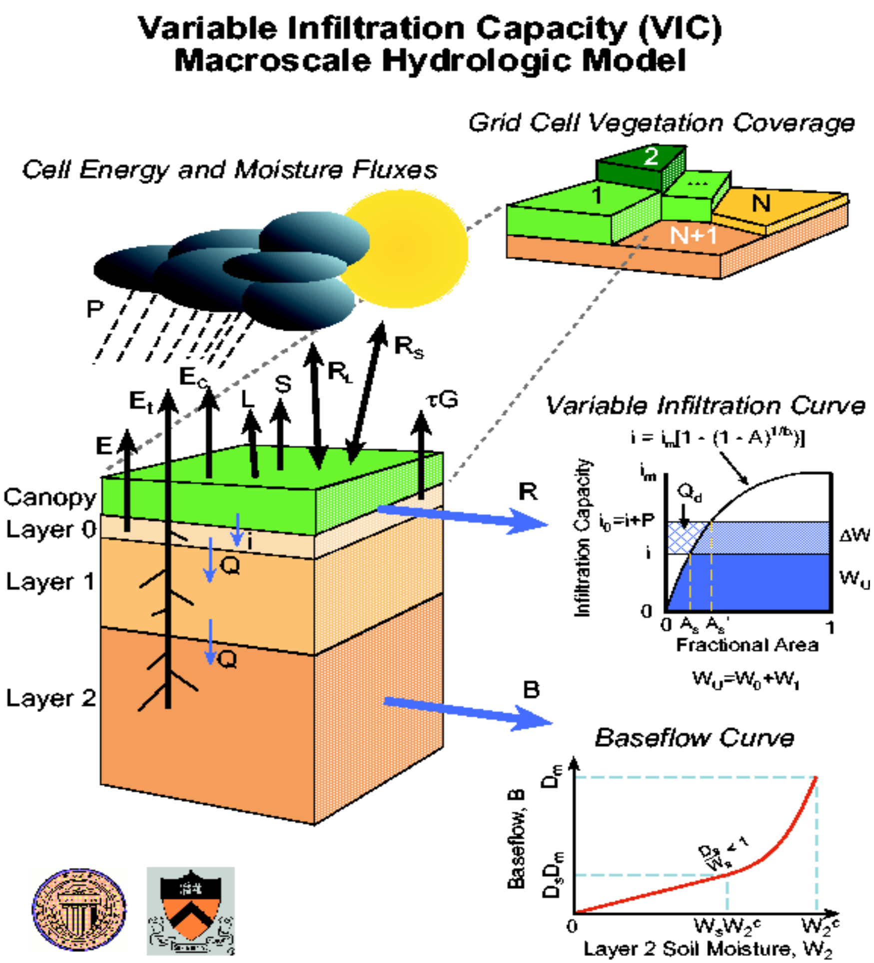
- Adjusts historic monthly timeseries to match CDF of GCM at each grid cell
- Forces historic daily timeseries to fit new monthly values
- Preserves most of the historical time series behavior
  - Storm size, storm location, interarrival, seasonality, time, etc.
- Two30-year time periods
  - 2040s and 2080s

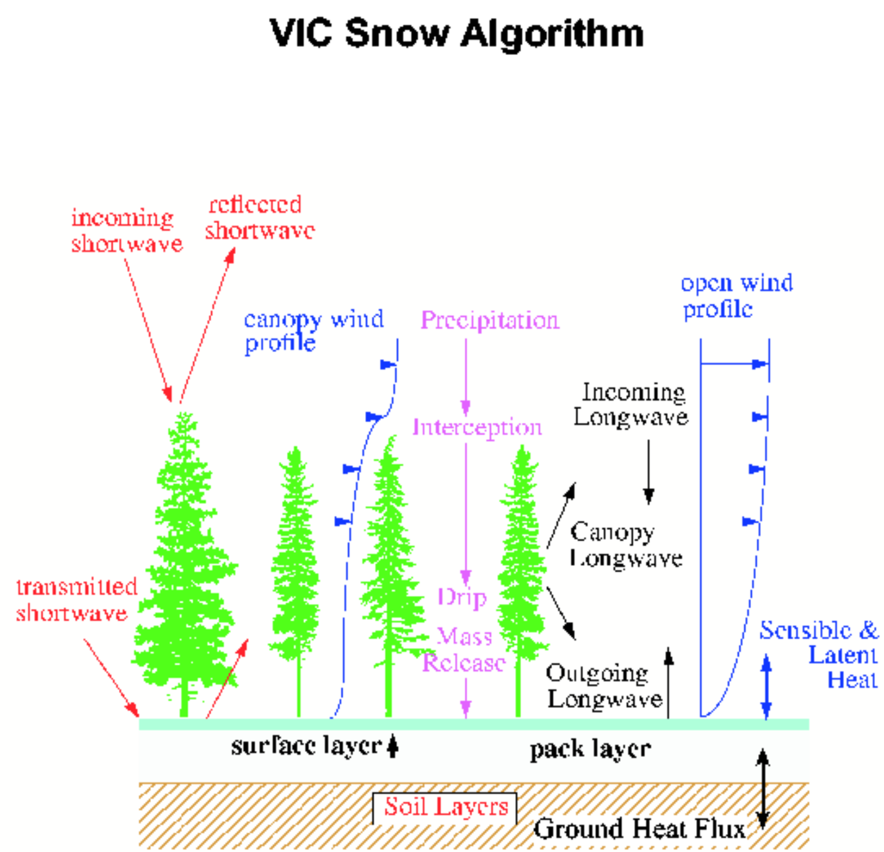
GETTING FROM THE GCMS TO INUNDATION MAPS

- Ultimately, we're trying to get inundation maps from GCM data
- So far we've got
  - Downscaled atmospheric forcings from climate models

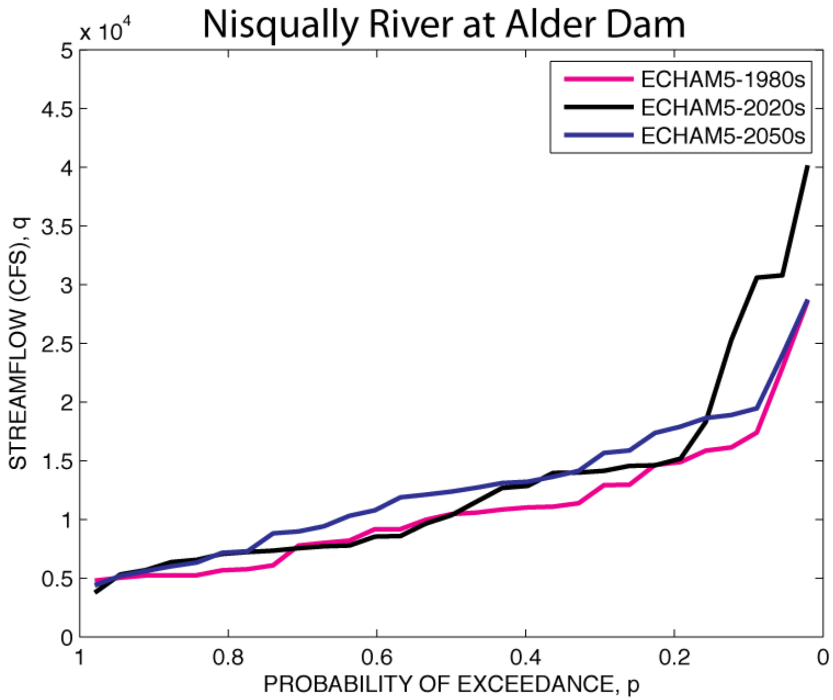


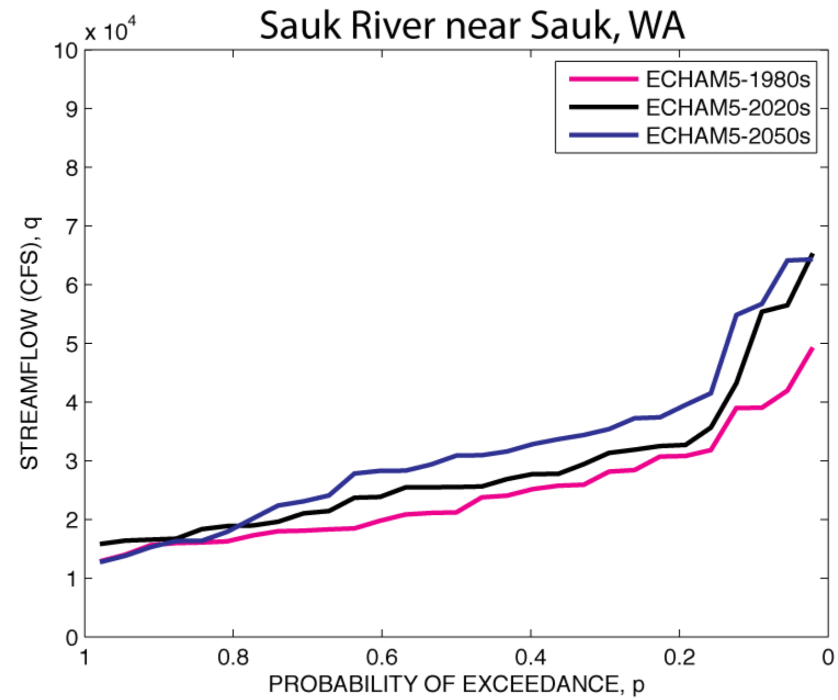
HYDROLOGIC MODELING





UNREGULATED HYDROLOGY





GETTING FROM THE GCMS TO INUNDATION MAPS

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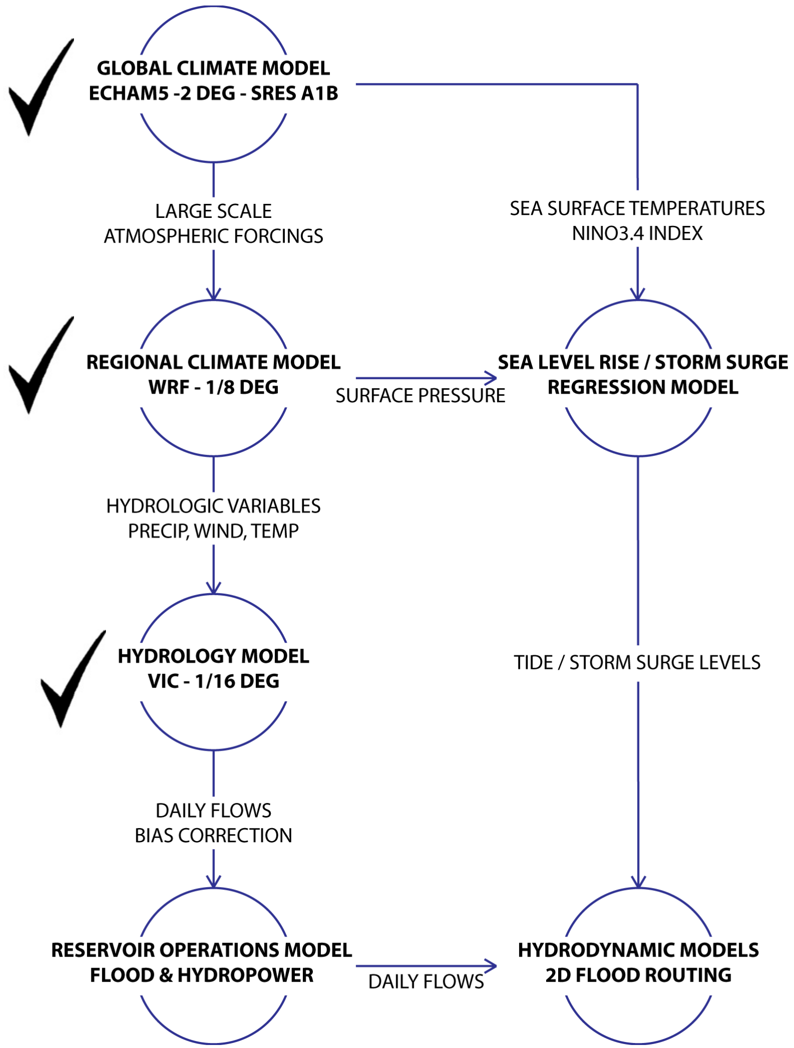
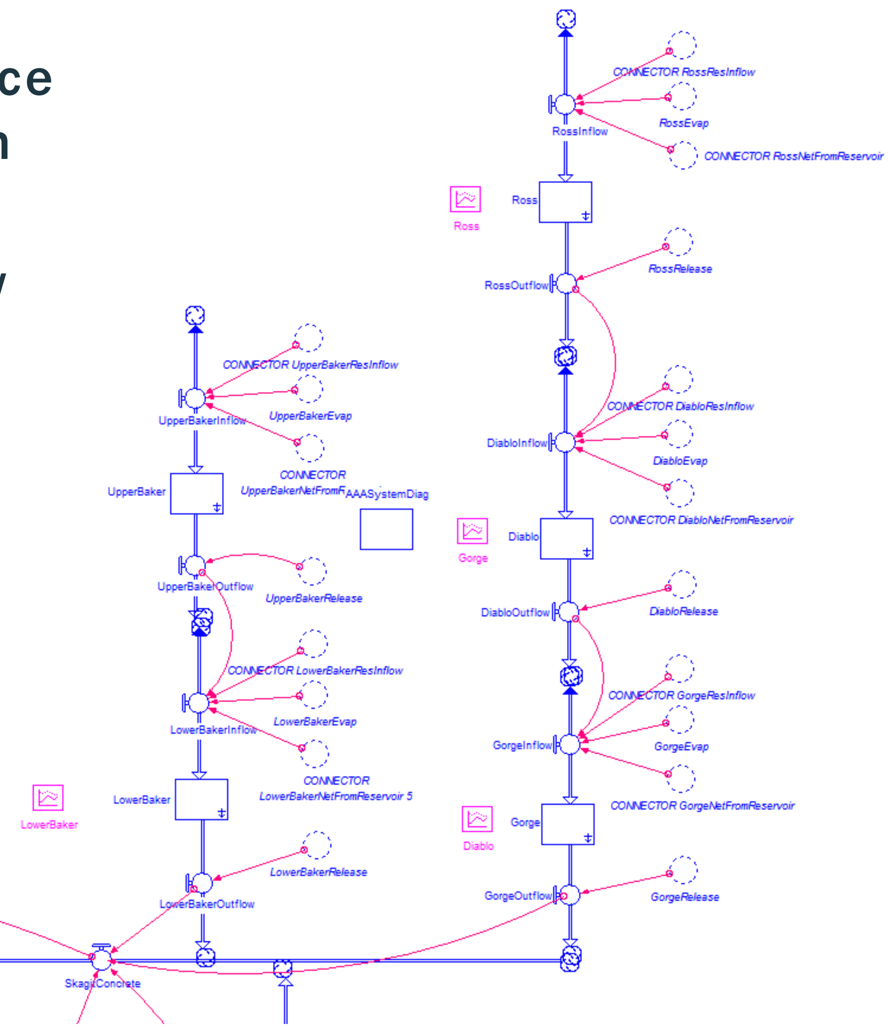
  - Downscaled atmospheric forcings from climate models
  - Unregulated streamflow projections

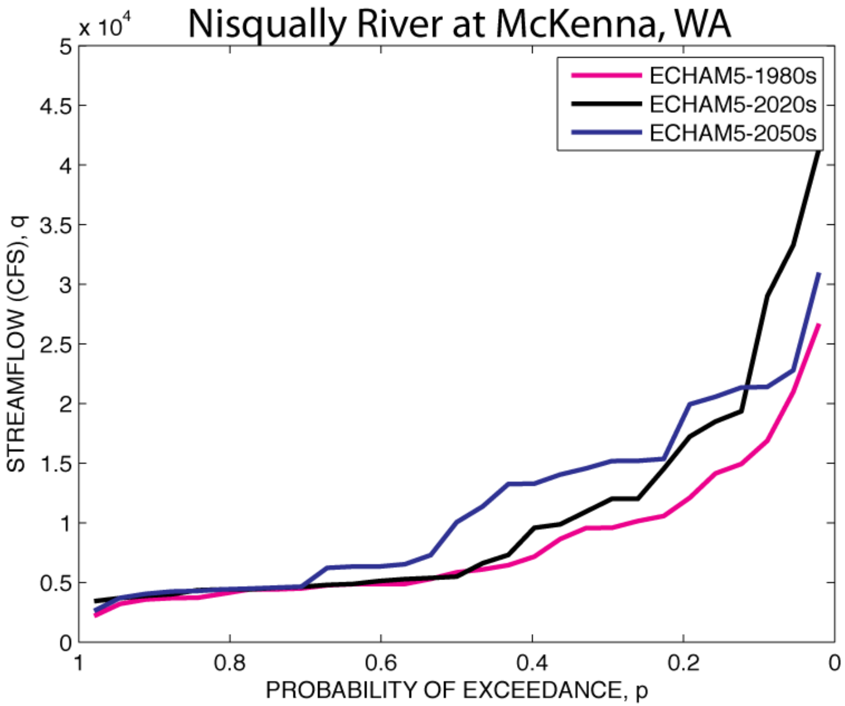


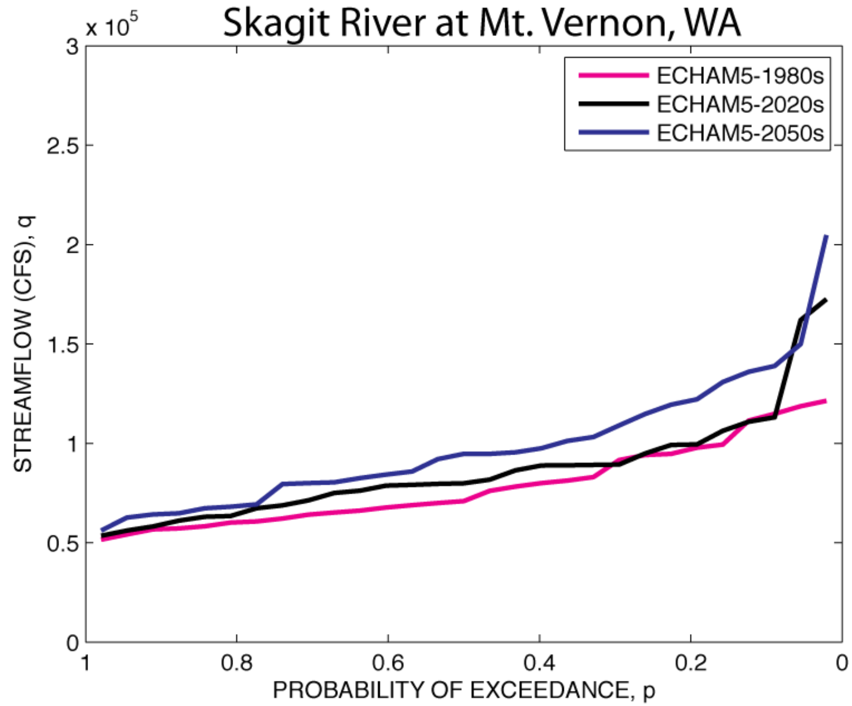
RESERVOIR MODELING

1. **Satisfy system mass balance and physical constraints on storage and releases.**
2. **Satisfy local minimum flow requirements.**
3. **Satisfy hydropower production demands.**
4. **Follow flood control rules and mimic flood control operations.**



REGULATED PEAK FLOWS





GETTING FROM THE GCMS TO INUNDATION MAPS

- Ultimately, we're trying to get inundation maps from GCM data
- So far we have:
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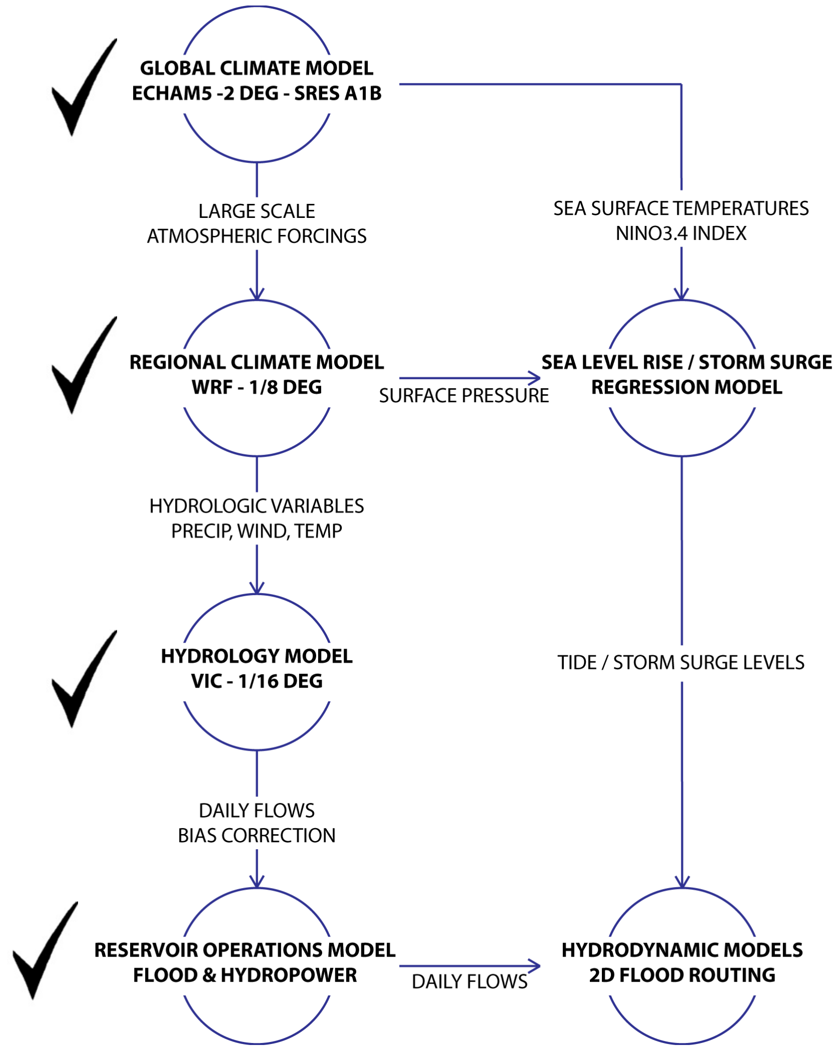
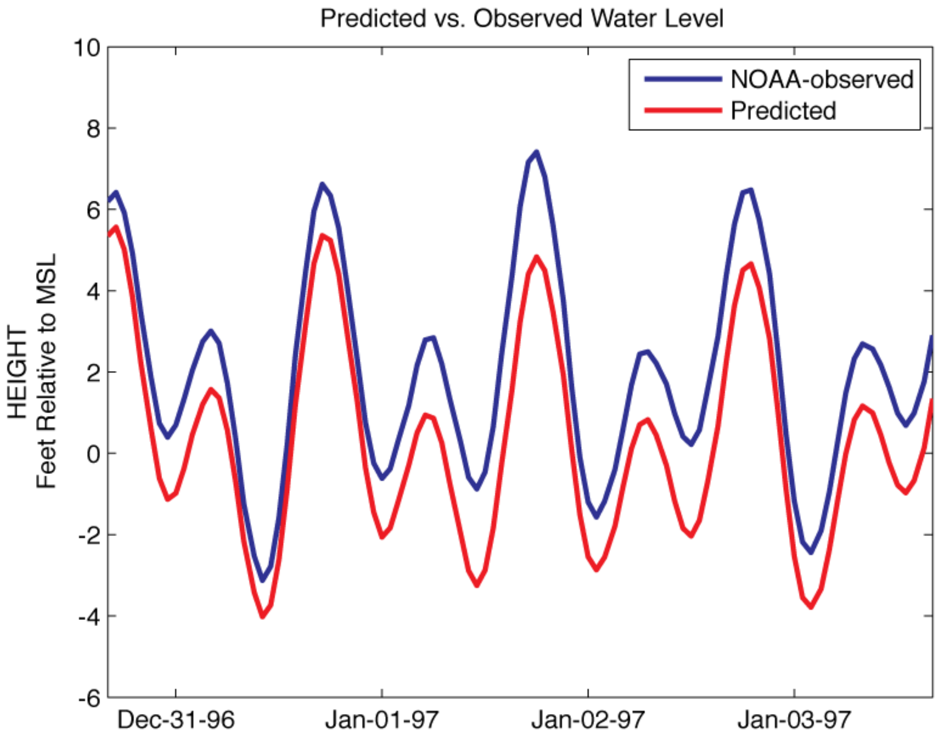
  - Unregulated streamflow projections
  - Regulated streamflow projections

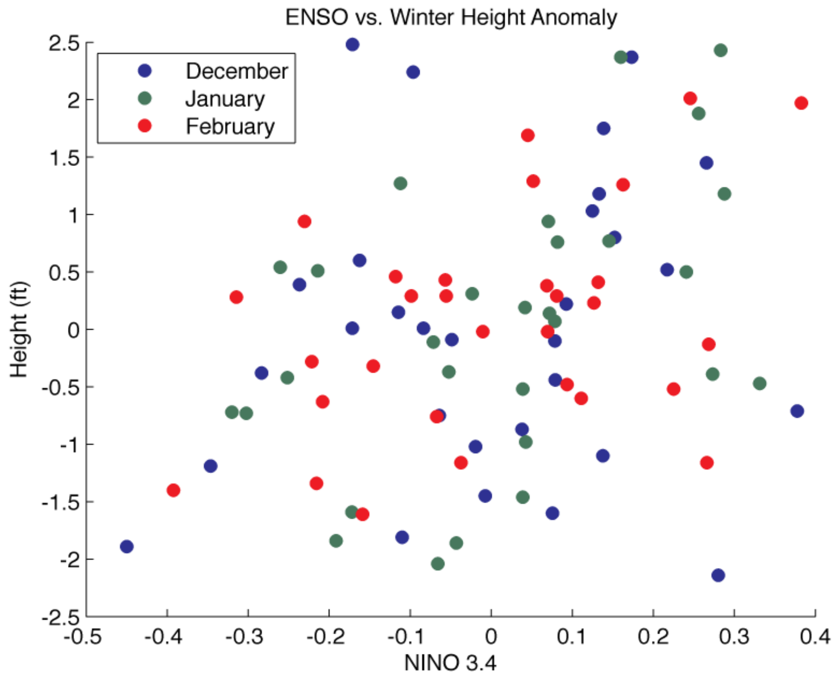


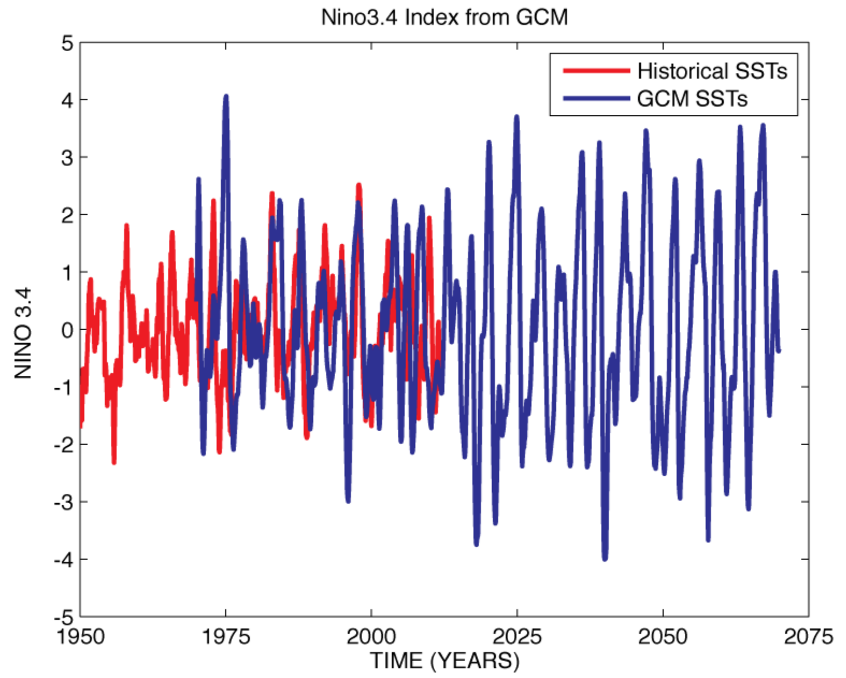
STORM SURGE
LINEAR REGRESSION APPROACH

1. Calculate anomalies and sort by month
2. Anomaly = f (Pressure, Pressure Patterns, ENSO)
   - Training Data: WRF-Reanalysis, observed ENSO
   - Forecast Data: WRF-ECHAM5 and ECHAM5 SSTs
3. Add forecasted anomalies and SLR to hourly tide projections



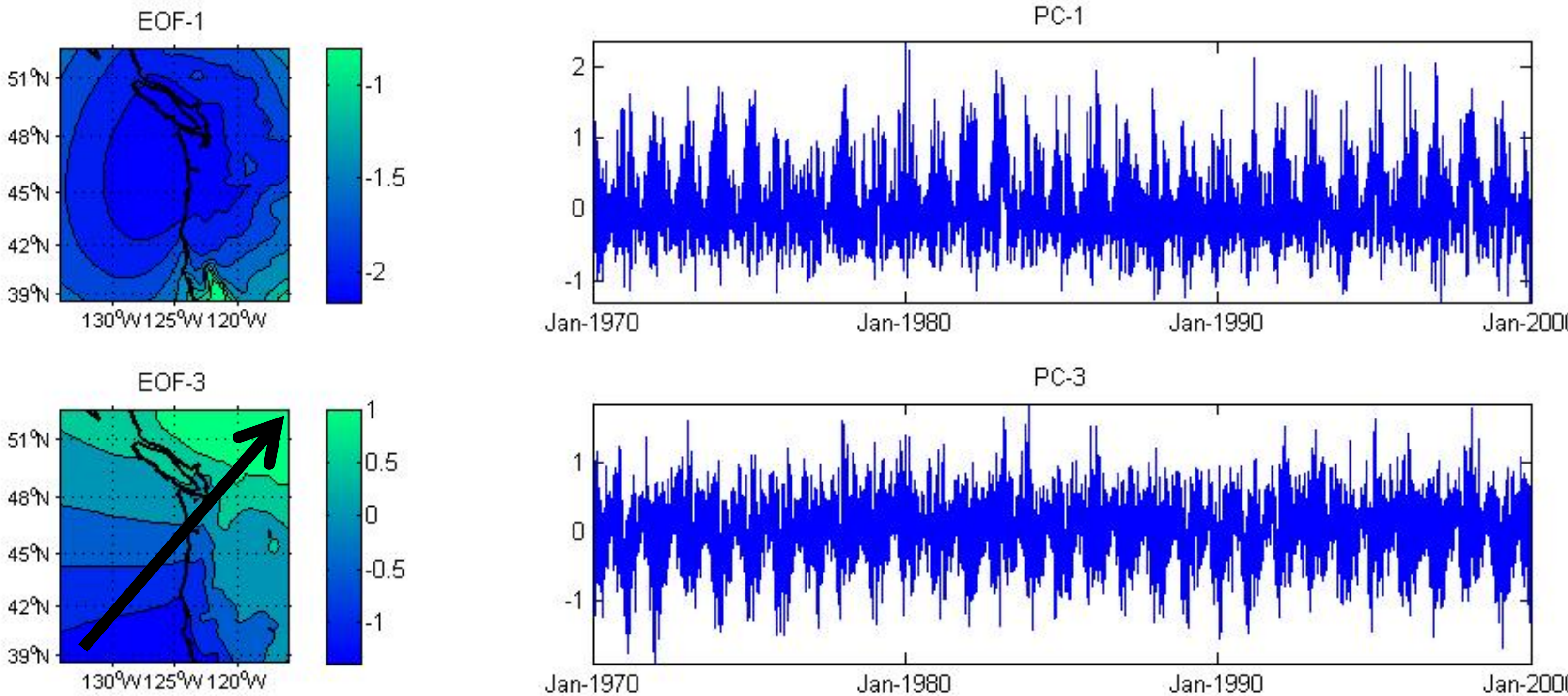
STORM SURGE
EL NINO SOUTHERN OSCILLATION





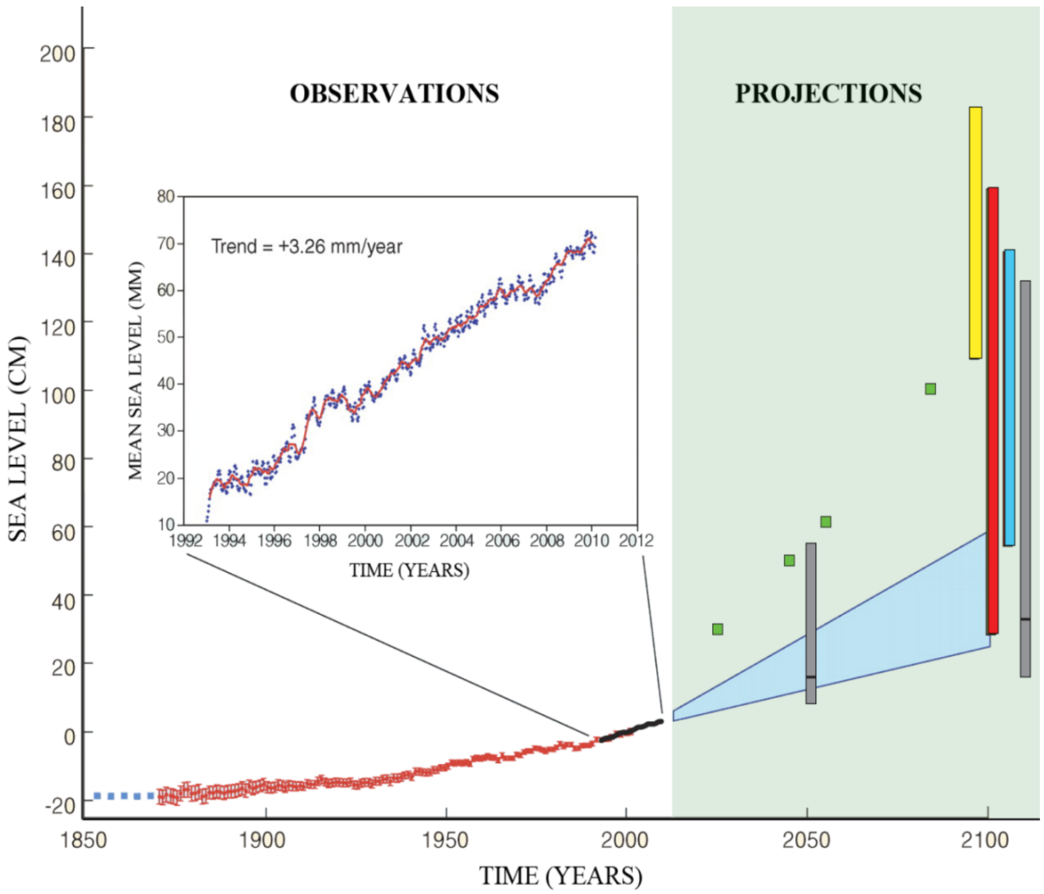
- Linear relationship between ENSO and Winter height anomaly
- Extracted Nino3.4 from GCM SSTs

STORM SURGE PRESSURE PATTERNS



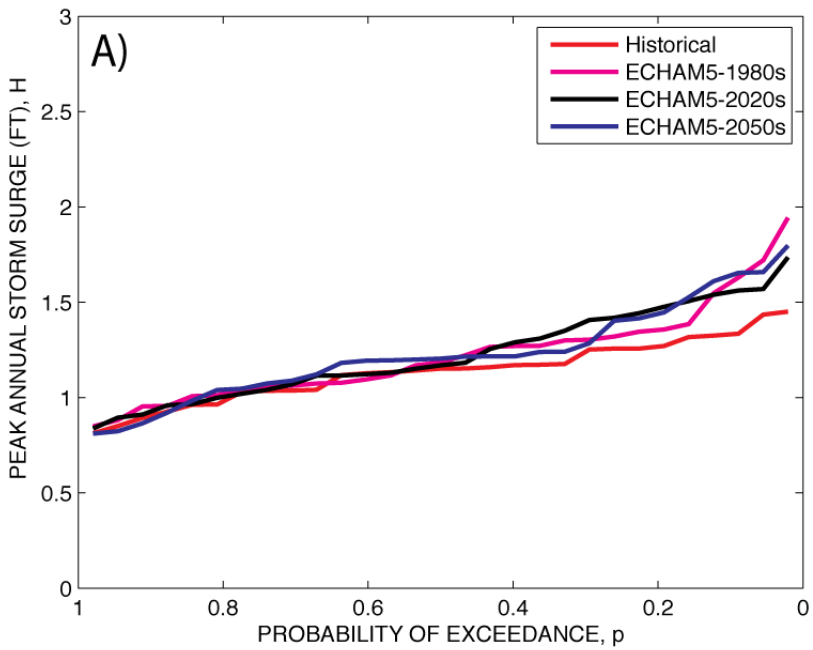
- Used singular value decomposition (SVD) to isolate important regional pressure patterns
- These time series represent the key modes of pressure variability that explain storm surge anomalies

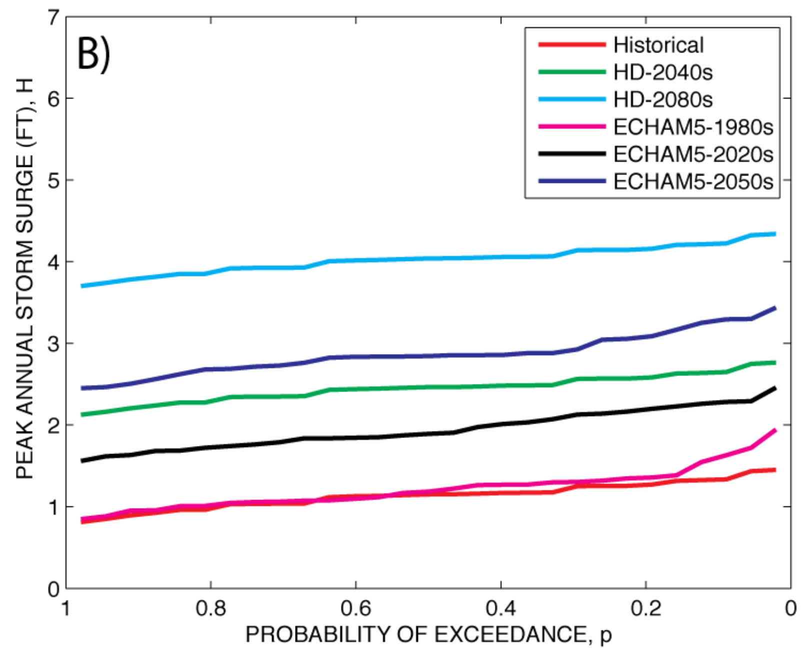
SEA LEVEL RISE



- Large range in SLR projections
- We used upper end of Mote et al., 2008 projections as a mid-high estimate

STORM SURGE AND SLR

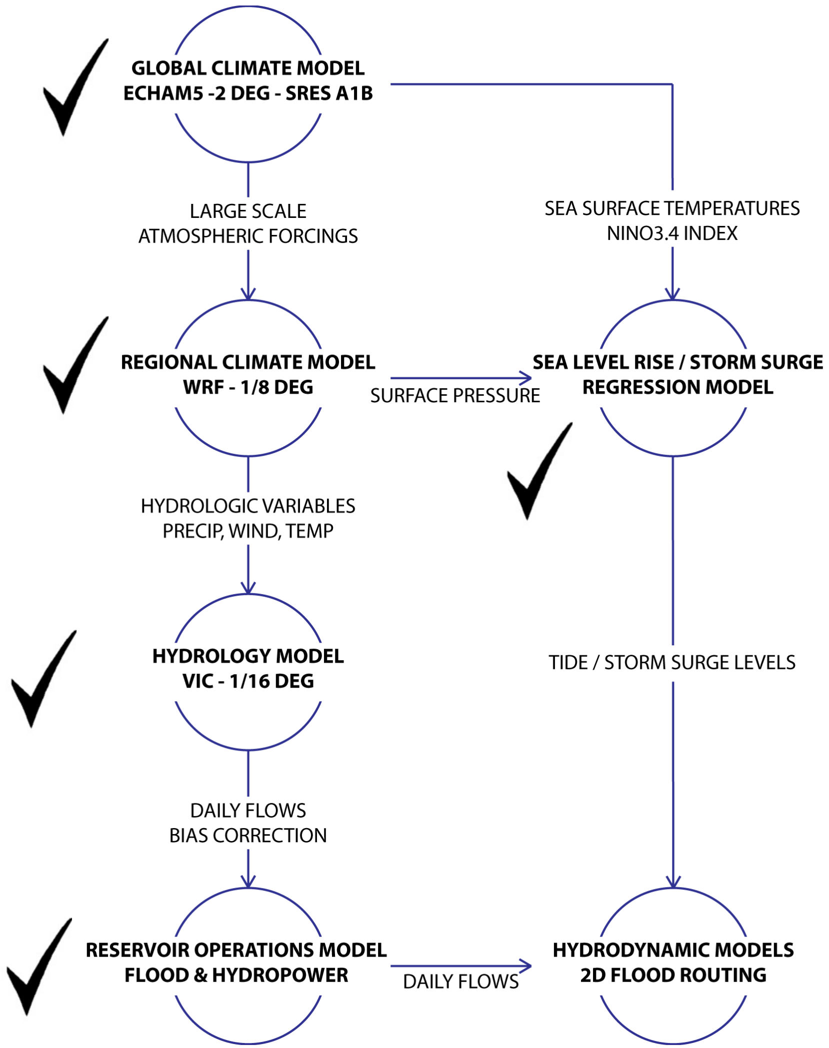




- Little to no change in the CDFs between RCM time periods
- SLR, by comparison, drastically changes the CDFs by shifting them all upward

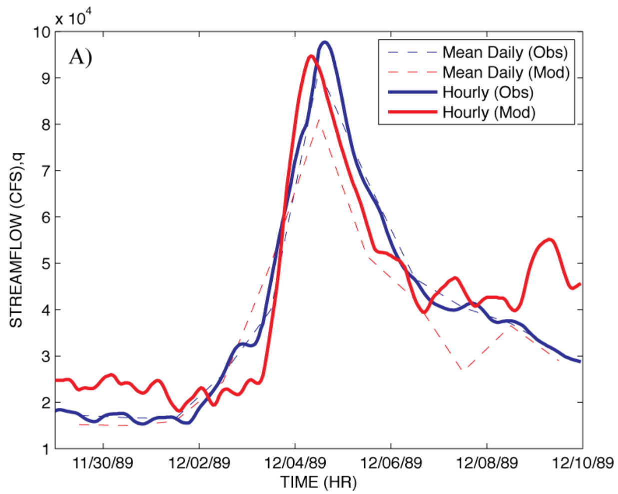
GETTING FROM THE GCMS TO INUNDATION MAPS

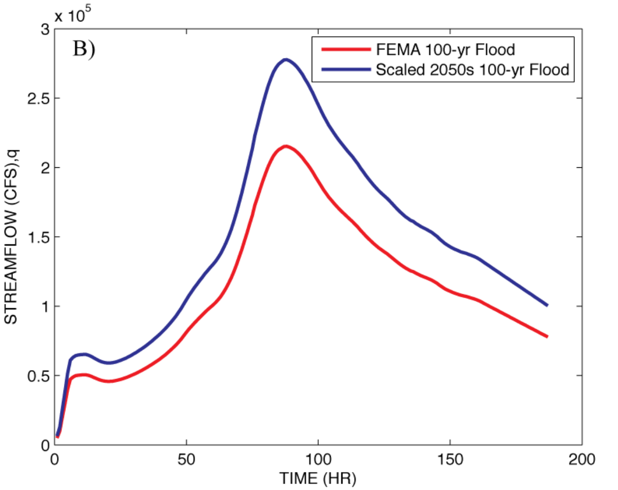
- Ultimately, we're trying to get inundation maps from GCM data
- So far we have:
  - Downscaled atmospheric forcings from climate models
  - Unregulated streamflow projections
  - Regulated streamflow projections
  - Hourly tide and storm surge projections



HOURLY DISAGGREGATION

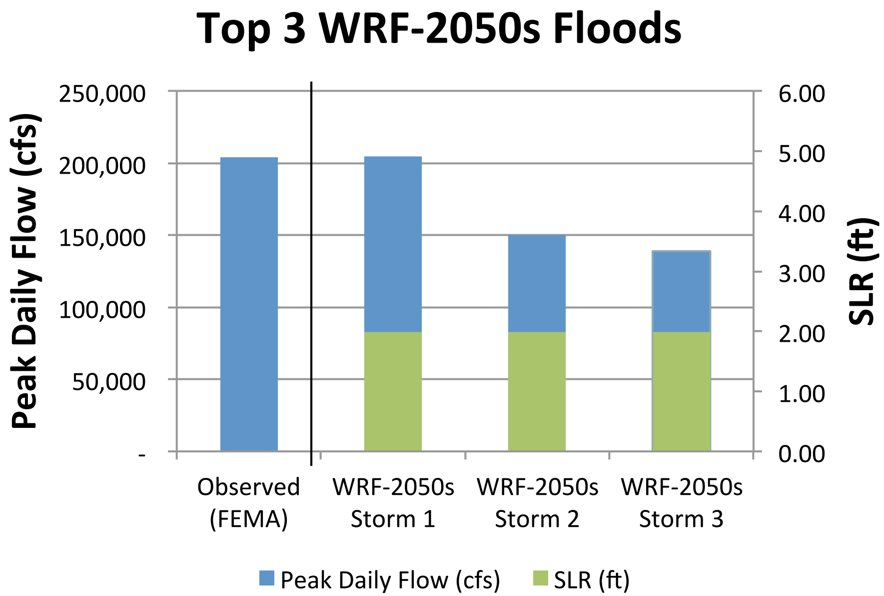
- WRF storms
  - **Goal**: Assess dynamics of flooding under completely different conditions (storm surge, SLR, hydrograph)
  - ***Approach***: *Steepness Index Unit Volume Flood Hydrograph Approach for Sub-Daily Flow Disaggregation*
- Scaled FEMA storms
  - **Goal**: Compare flood extents and depths between different time periods (e.g. Historical and 2050s)
  - ***Approach***: Scale by relative increase in 100-yr flood based on GEVD fit to each 30-yr time period

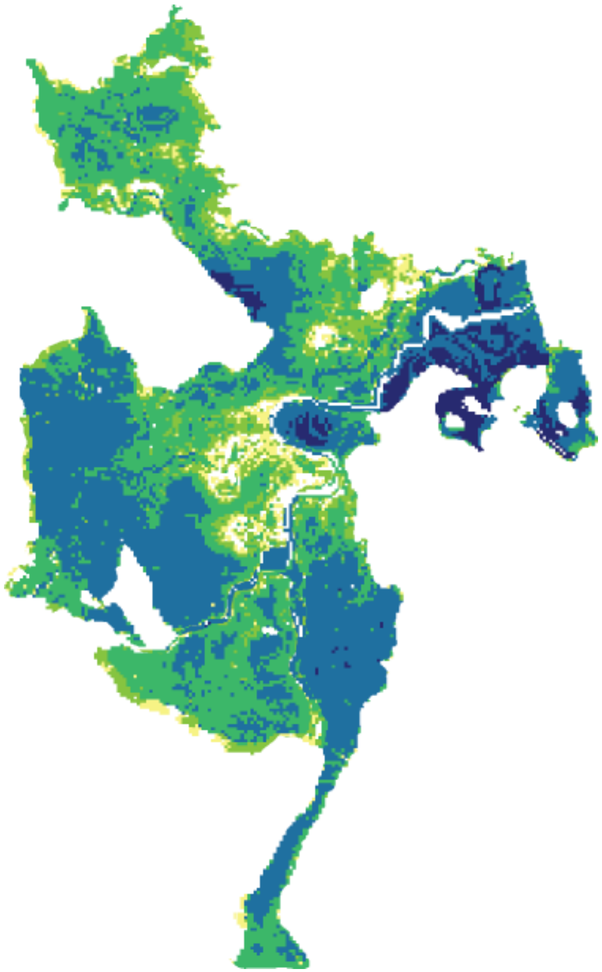




HYDRODYNAMIC MODELING

- Skagit Model developed by USACE and FEMA
- 2D hydrodynamic model, Flo2D
- Simulates channel and overbank flow in lower Skagit River Basin
- Includes current levees and dikes





WRF-2050S FLOOD 1
ALL LEVEES INTACT

Peak Daily Flow, cfs

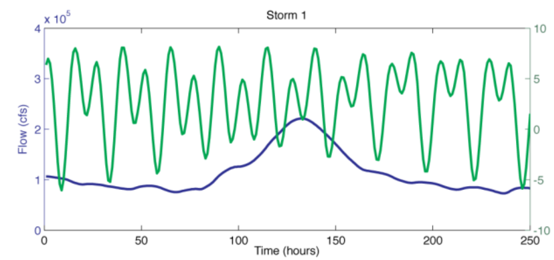
204,718

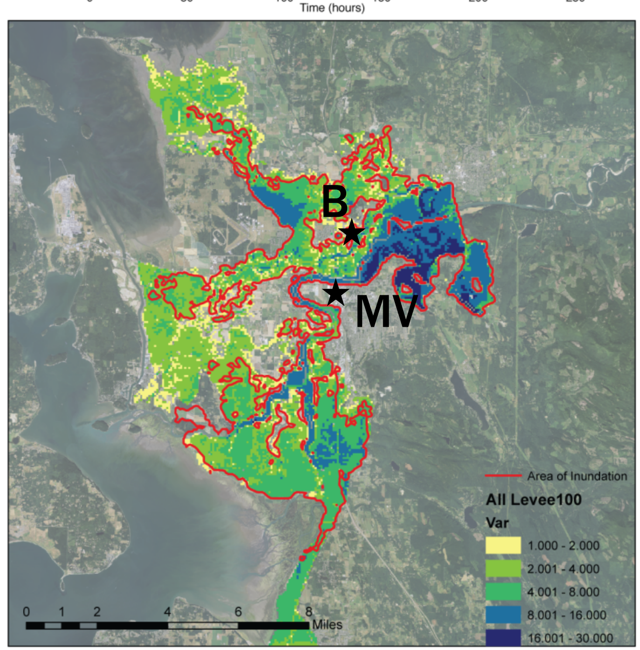
Sea Level Rise, ft

1.99

Storm Surge, ft

0.90





1/30/2069

Inundation, acres (Relative to 100yrFEMA)

60,544
(1.43)

Mt. Vernon Depth, ft

0.00

Burlington Depth, ft

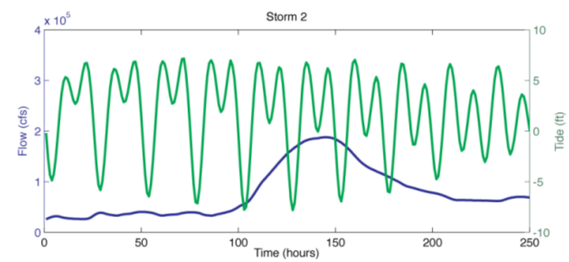
1.58

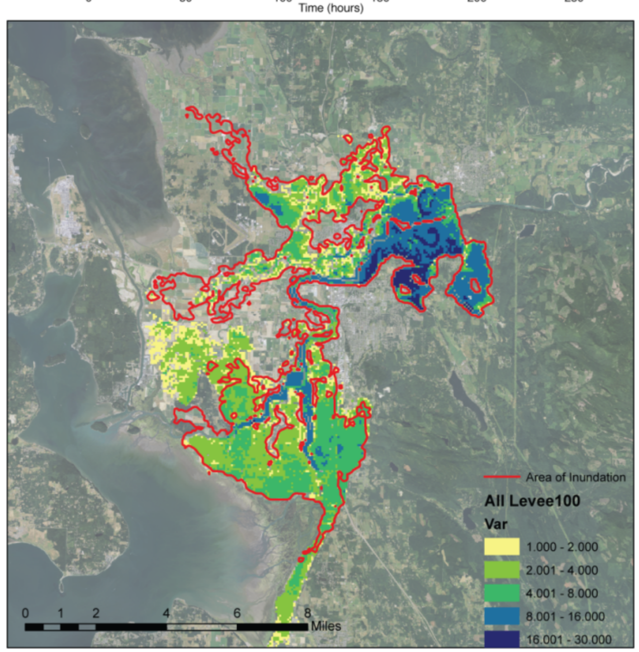
WRF-2050S FLOOD 2
ALL LEVEES INTACT

Peak Daily Flow, cfs
149,890

Sea Level Rise, ft
1.99

Storm Surge, ft
-0.59





2/4/2053

Inundation, acres (Relative to 100yrFEMA)
43,052 (1.02)

Mt. Vernon Depth, ft
0.00

Burlington Depth, ft
0.00

WRF-2050S FLOOD 3
ALL LEVEES INTACT

Peak Daily Flow, cfs

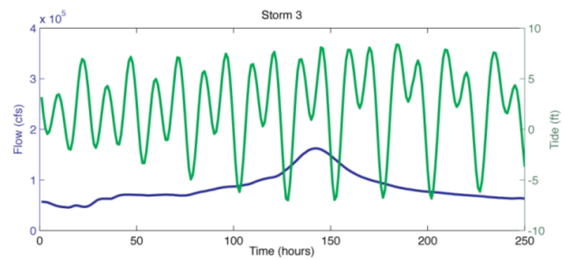
138,945

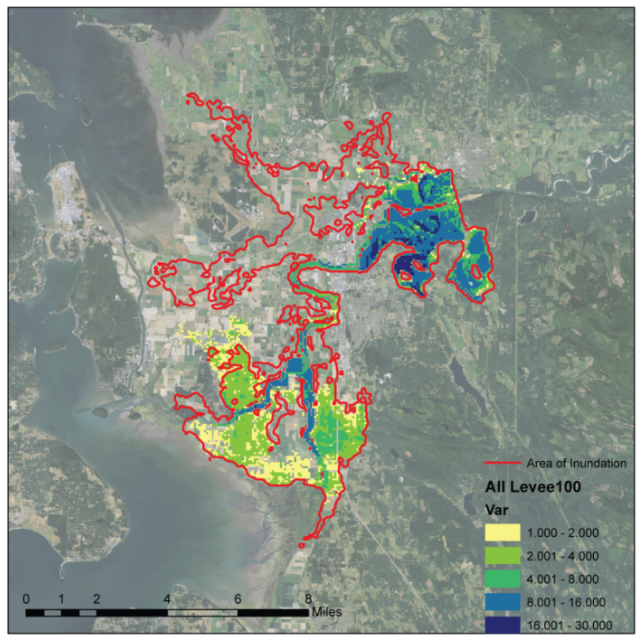
Sea Level Rise, ft

1.99

Storm Surge, ft

0.31





11/18/2047

Inundation, acres (Relative to 100yrFEMA)

22,527
(0.53)

Mt. Vernon Depth, ft

0.00

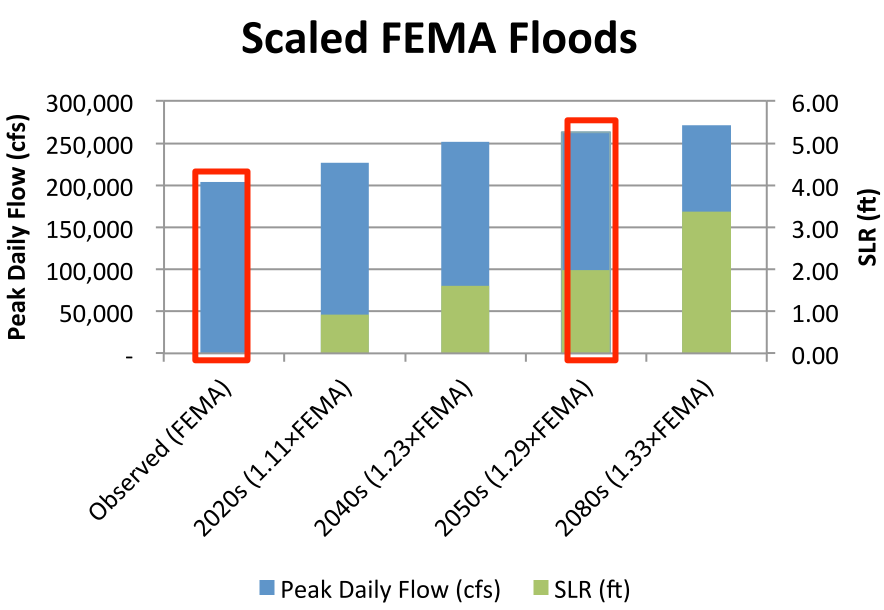
Burlington Depth, ft

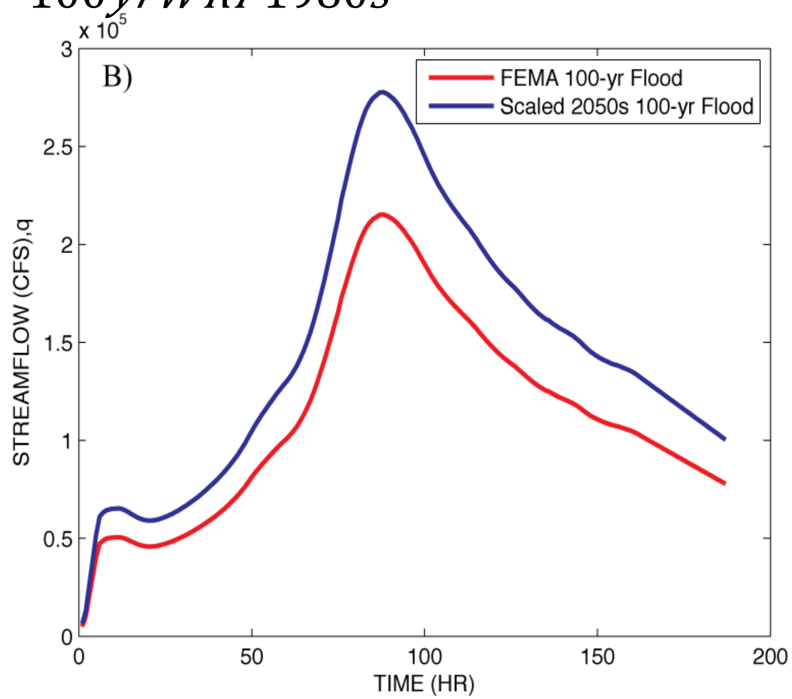
0.00

100 YEAR FLOOD MAPPING

- Applied relative changes in 100-year flood to FEMA hydrograph
- Eliminates model bias in peak flows
- Performed composite flood mapping for 2050s (7 levee failure scenarios)

$$FEMA2050s = FEMA \times 100yrWRF2050s/100yrWRF1980s$$





FEMA 100-YEAR FLOOD
ALL LEVEES INTACT

Peak Daily Flow, cfs

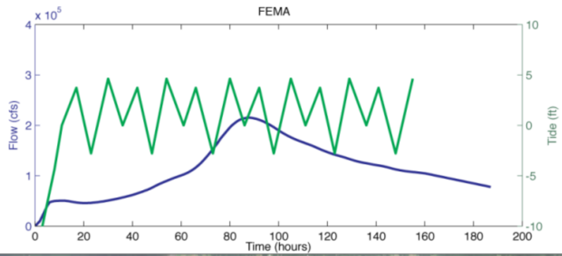
203,835

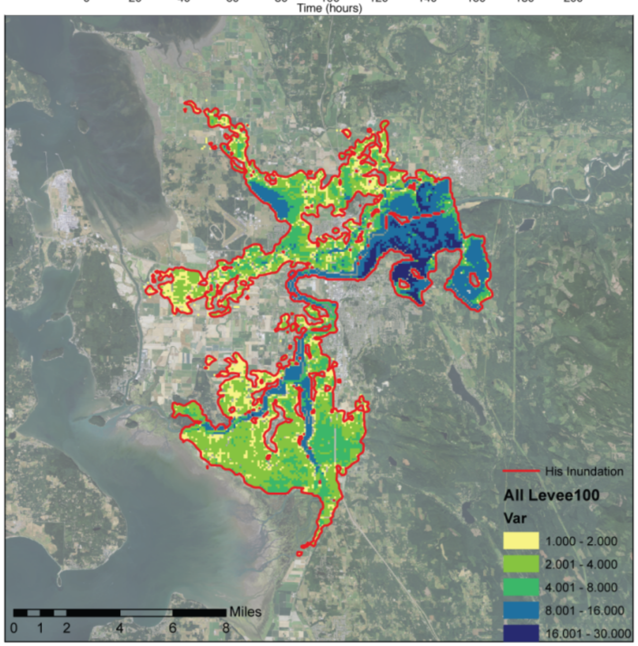
Sea Level Rise, ft

0.00

Storm Surge, ft

1.5





FEMA - His

Inundation, acres (Relative to His)

42,266
(1.00)

Mt. Vernon Depth, ft

0.00

Burlington Depth, ft

0.77

2020S 100-YEAR FLOOD
ALL LEVEES INTACT

Peak Daily Flow, cfs

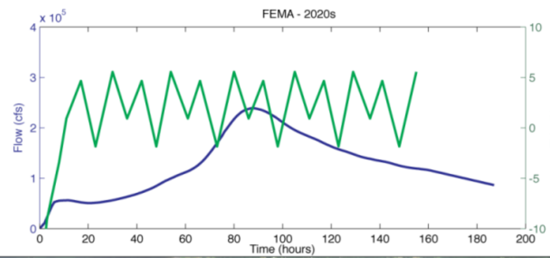
226,697

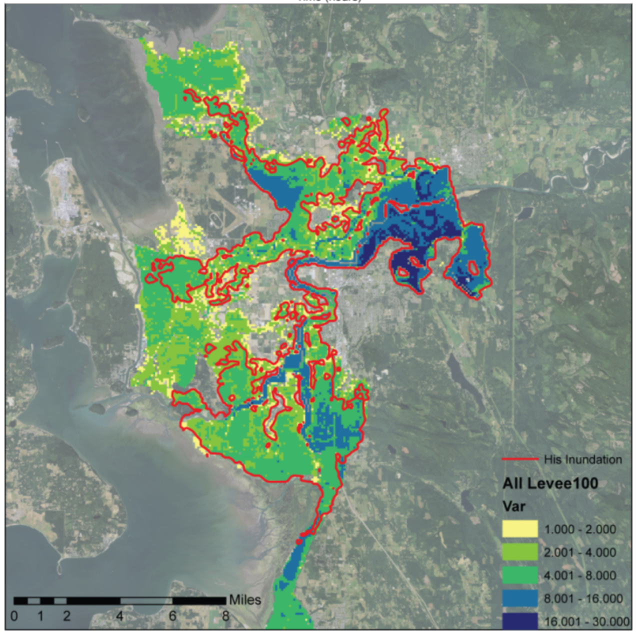
Sea Level Rise, ft

0.93

Storm Surge, ft

1.5





FEMA – 2020s

Inundation, acres (Relative to His)

64,878
(1.53)

Mt. Vernon Depth, ft

0.00

Burlington Depth, ft

1.89

2040S 100-YEAR FLOOD
ALL LEVEES INTACT

Peak Daily Flow, cfs

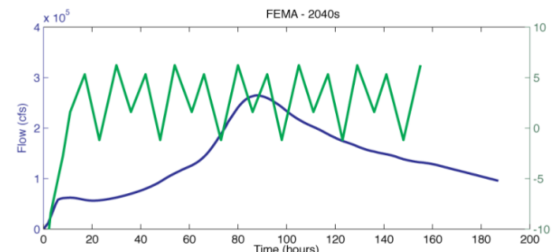
251,441

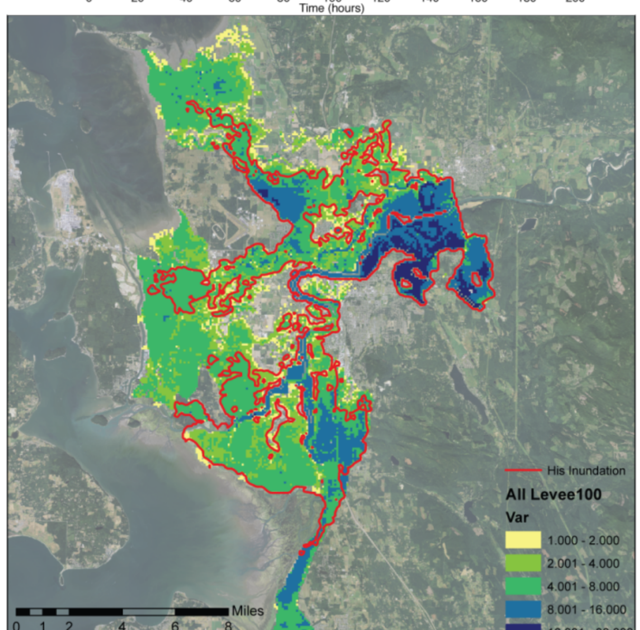
Sea Level Rise, ft

1.60

Storm Surge, ft

1.5





FEMA – 2040s

Inundation, acres (Relative to His)

71,236
(1.69)

Mt. Vernon Depth, ft

0.45

Burlington Depth, ft

2.40

2050S 100-YEAR FLOOD
ALL LEVEES INTACT

Peak Daily Flow, cfs

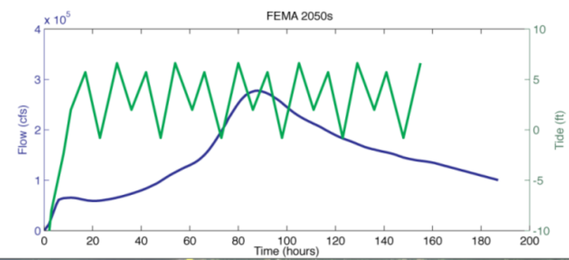
263,016

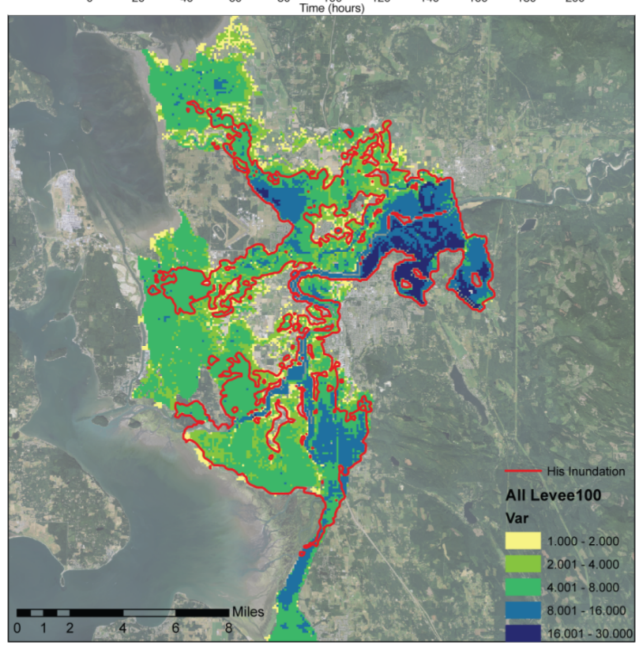
Sea Level Rise, ft

1.99

Storm Surge, ft

1.5





FEMA – 2050s

Inundation, acres (Relative to His)

72,555
(1.72)

Mt. Vernon Depth, ft

0.89

Burlington Depth, ft

2.55

2080S 100-YEAR FLOOD ALL LEVEES INTACT

Peak Daily Flow, cfs

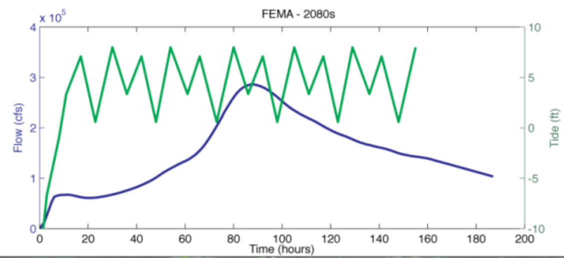
270,803

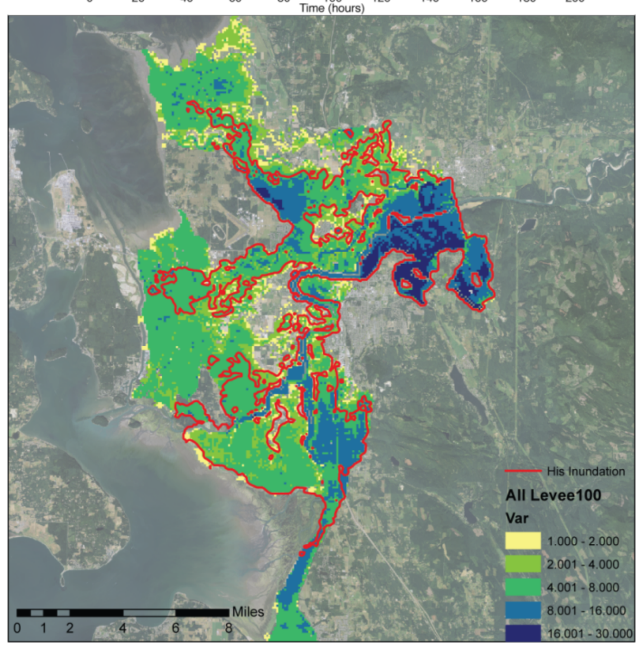
Sea Level Rise, ft

3.36

Storm Surge, ft

1.5





FEMA – 2080s

Inundation, acres (Relative to His)

73,914
(1.75)

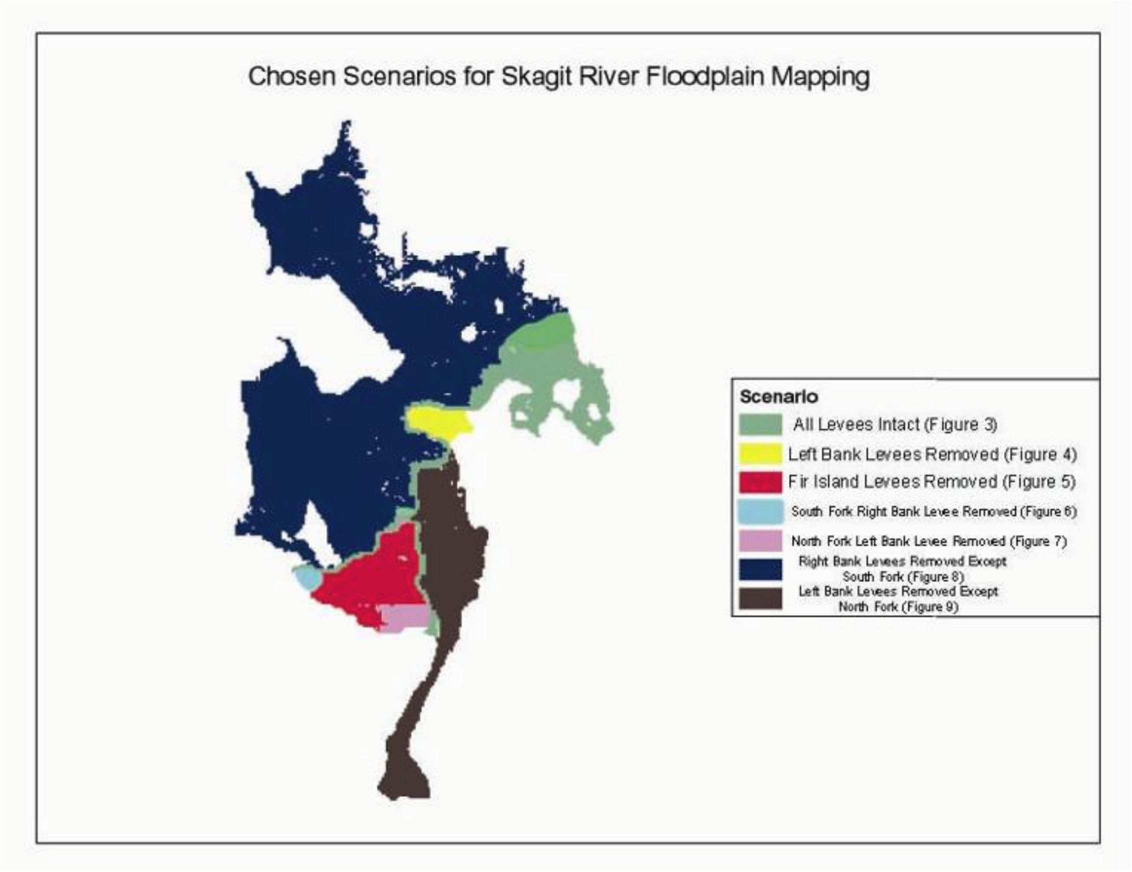
Mt. Vernon Depth, ft

0.98

Burlington Depth, ft

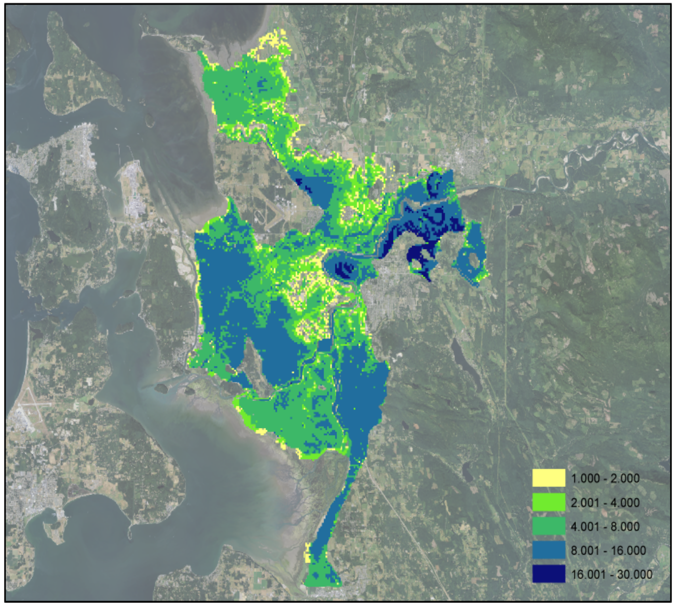
2.72

COMPOSITE FLOOD MAPS
7 LEVEE FAILURE SCENARIOS



COMPOSITE FLOOD MAPS
7 LEVEE FAILURE SCENARIOS

FEMA Composite Map



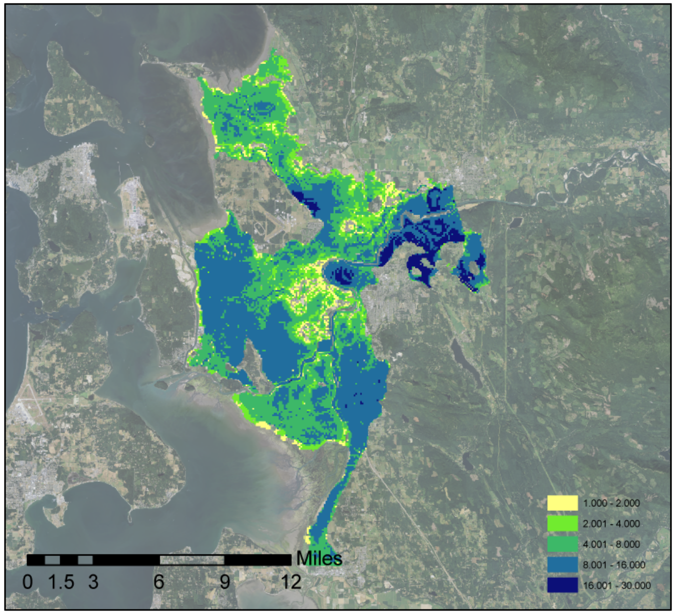
Mt. Vernon Depth, ft

11.31

Burlington Depth, ft

2.79

2050s Composite Map



Mt. Vernon Depth, ft

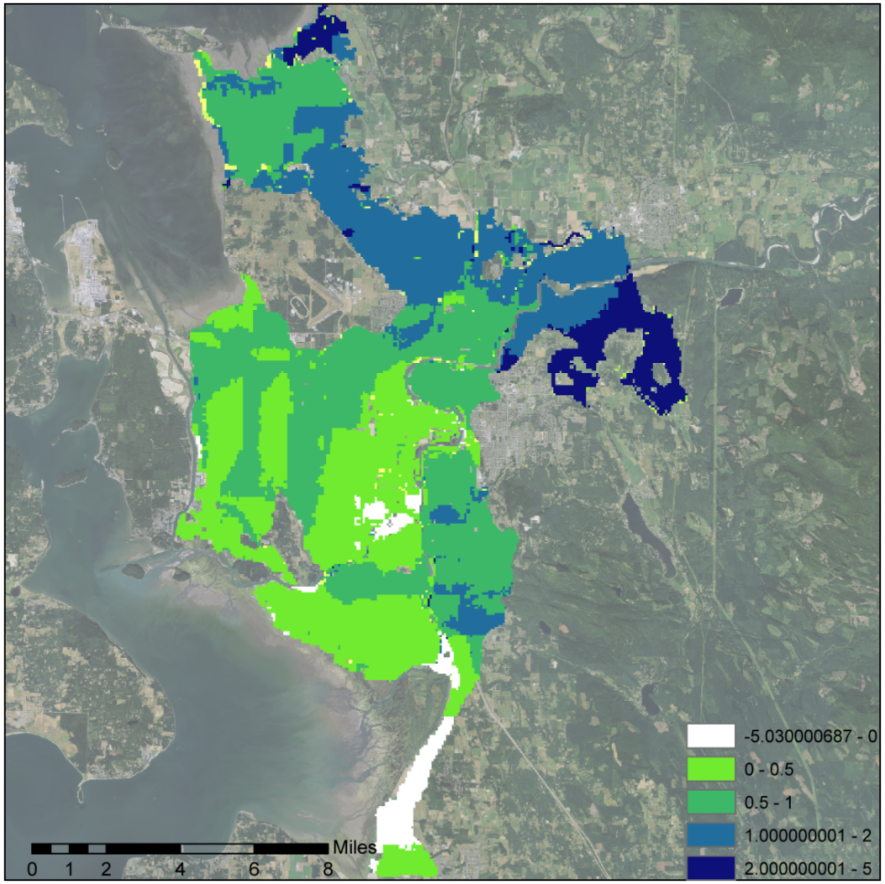
12.02

Burlington Depth, ft

3.70

DIFFERENCE BETWEEN COMPOSITE FLOOD MAPS

(2050s Composite Map – FEMA Composite Map)



Mt. Vernon Depth, ft

0.71

Burlington Depth, ft

0.91

WHAT WE KNEW

- Climate change is expected to increase flood magnitudes, especially in transient mixed rain-snow basins.
  - 100-yr unregulated floods in Skagit and Nisqually Rivers could increase upwards of 50% by the 2080s.
- Sea Level Rise will increase base sea levels.
  - Projections range from 20 to 200 cm by 2100.

WHAT WE KNOW NOW

- Future storm surge, brought on by barometric and wind effects, is not expected to change significantly.
- Sea level rise is expected to influence extreme water levels much more than changes in storm surge.
- Inundation from flooding in the Skagit is expected to increase by up to 72% by the 2050s given combined SLR and increased flood magnitudes.
- Average depth in 100-yr flood map increases by 10 inches when 2050s flood and SLR are included.
- Using a scenario based approach is an effective way to understand changes in flood magnitudes over time.

FUTURE WORK

- Hydrodynamic modeling in Nisqually River.
- Investigate FEMA model domain size.
- The uncertainty in SLR estimates is a problem.
- More realizations of GCM/RCM/Hydrology models are necessary to find clear consensus in changes.
- ENSO relationship to flooding. Teleconnection may not be present in GCMs.
- Bias in absolute value of flooding is a problem for inundation mapping.

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  - Eric Salathé
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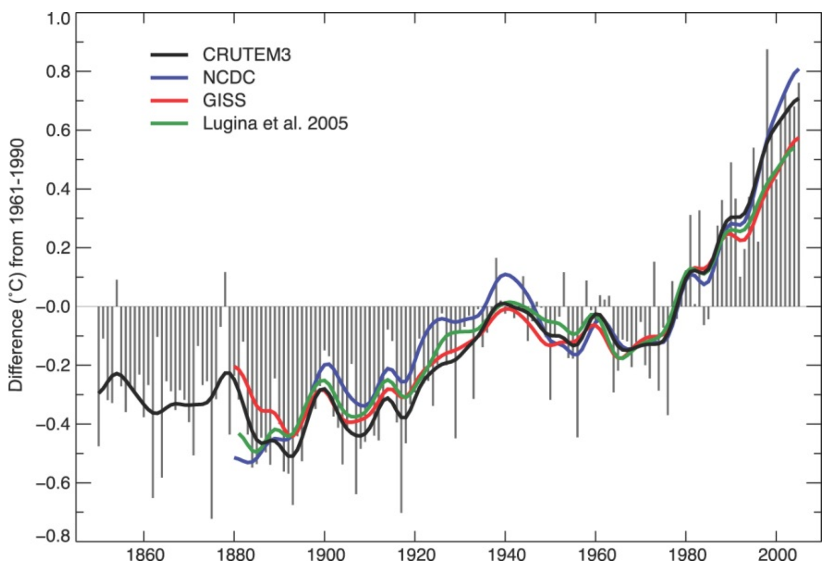
  - Roger Fuller
  - Eric Grossman

QUESTIONS?

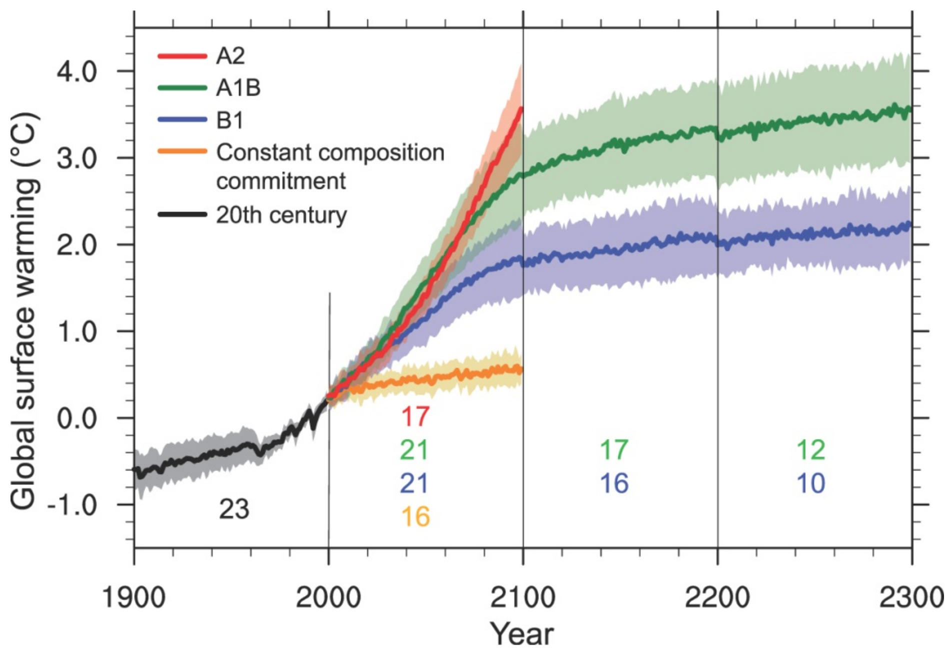
EXTRAS

GLOBAL CLIMATE CHANGE

20th century warming between 0.75 and 1°C



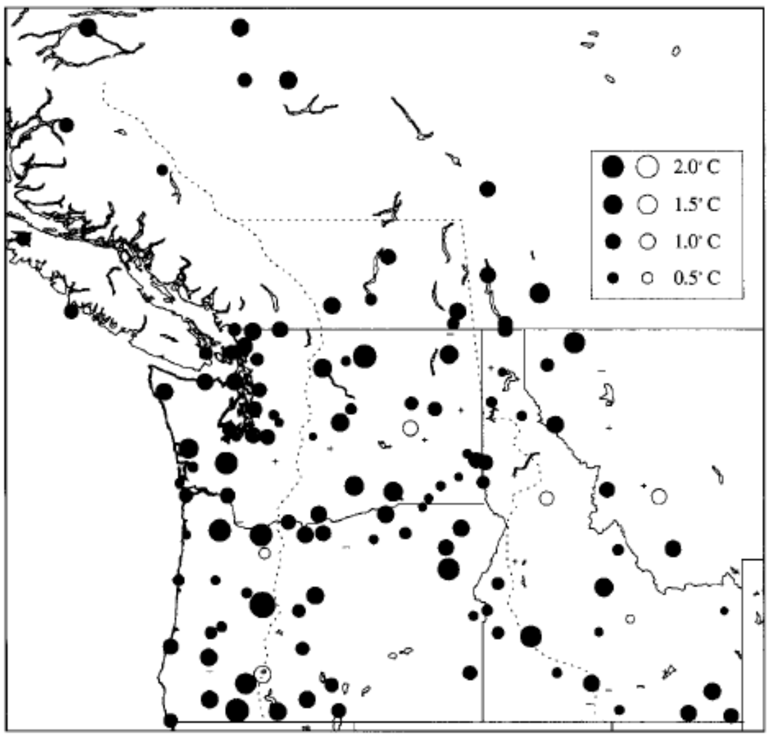
21th century warming between 1.5 and 3°C



Source: IPCC, 2007

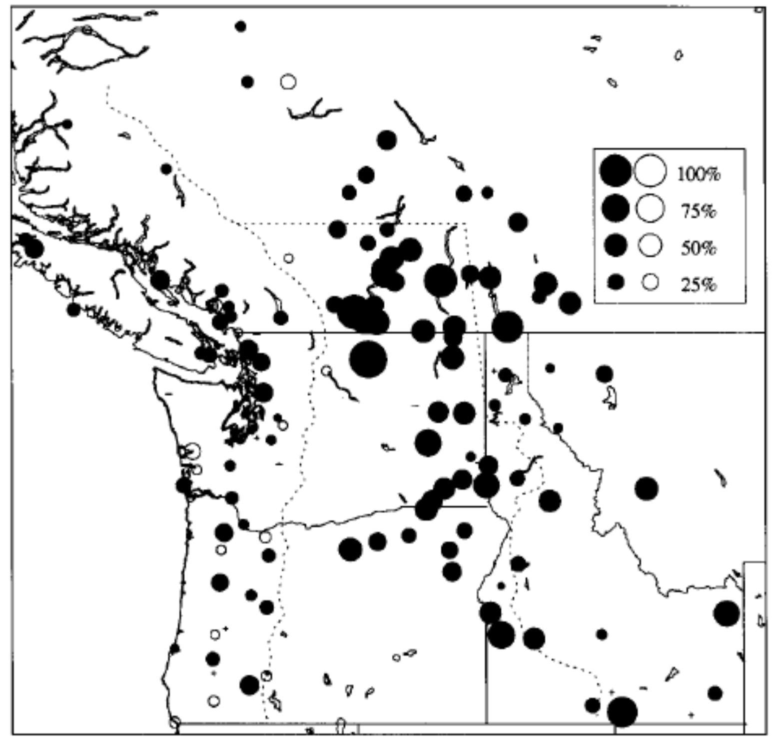
OBSERVED CLIMATE CHANGE IN THE PNW

Temperature



20th century trends 0.7-0.9 ° C

Precipitation

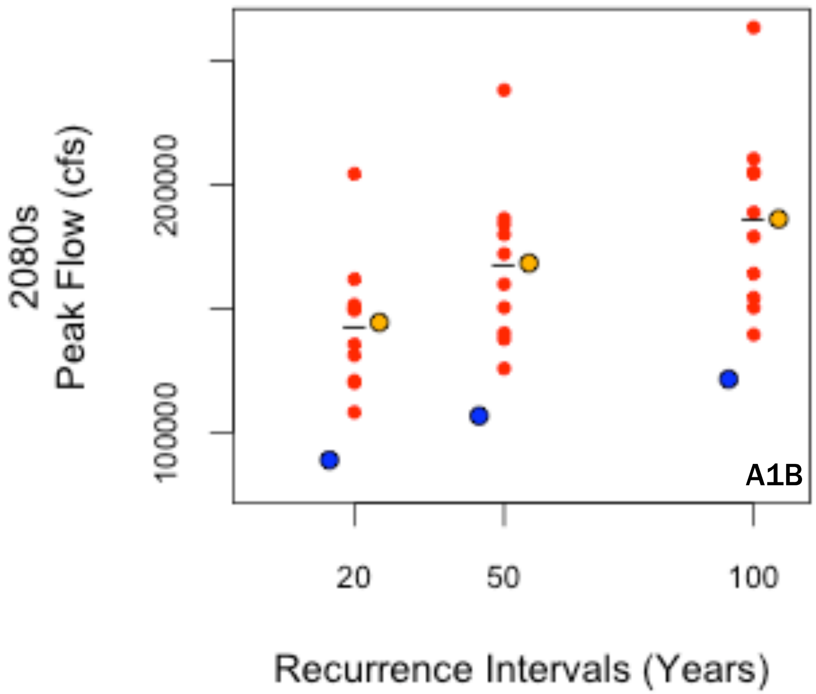


21st century trends 13-38%

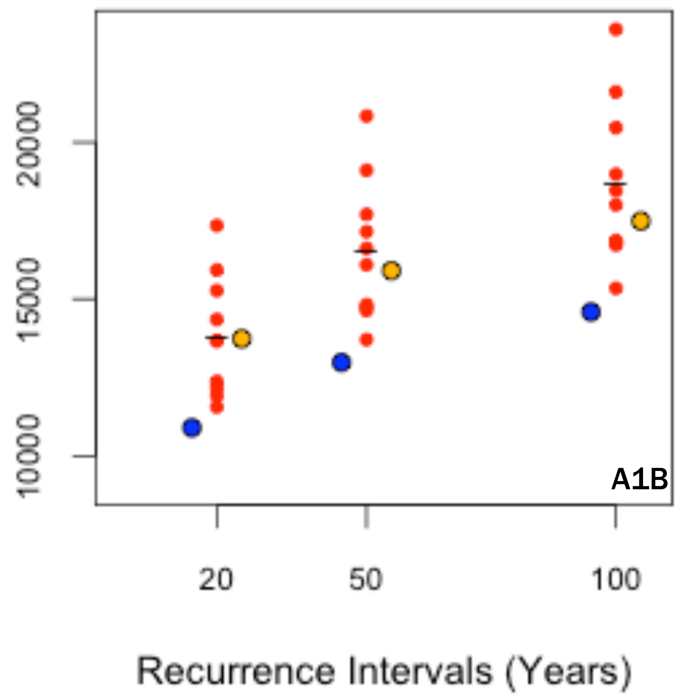
Source: Mote, 2003

UNREGULATED FLOODING

Skagit River at Mt. Vernon

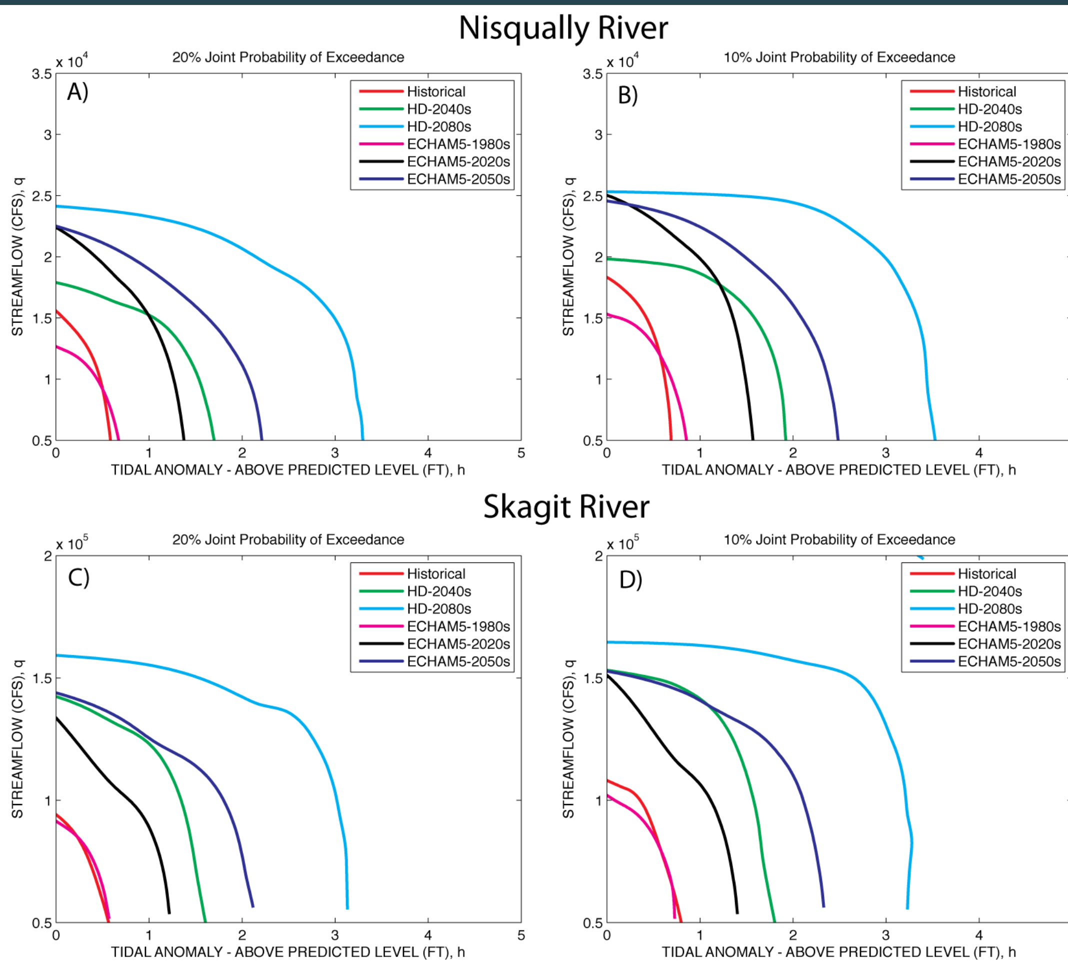


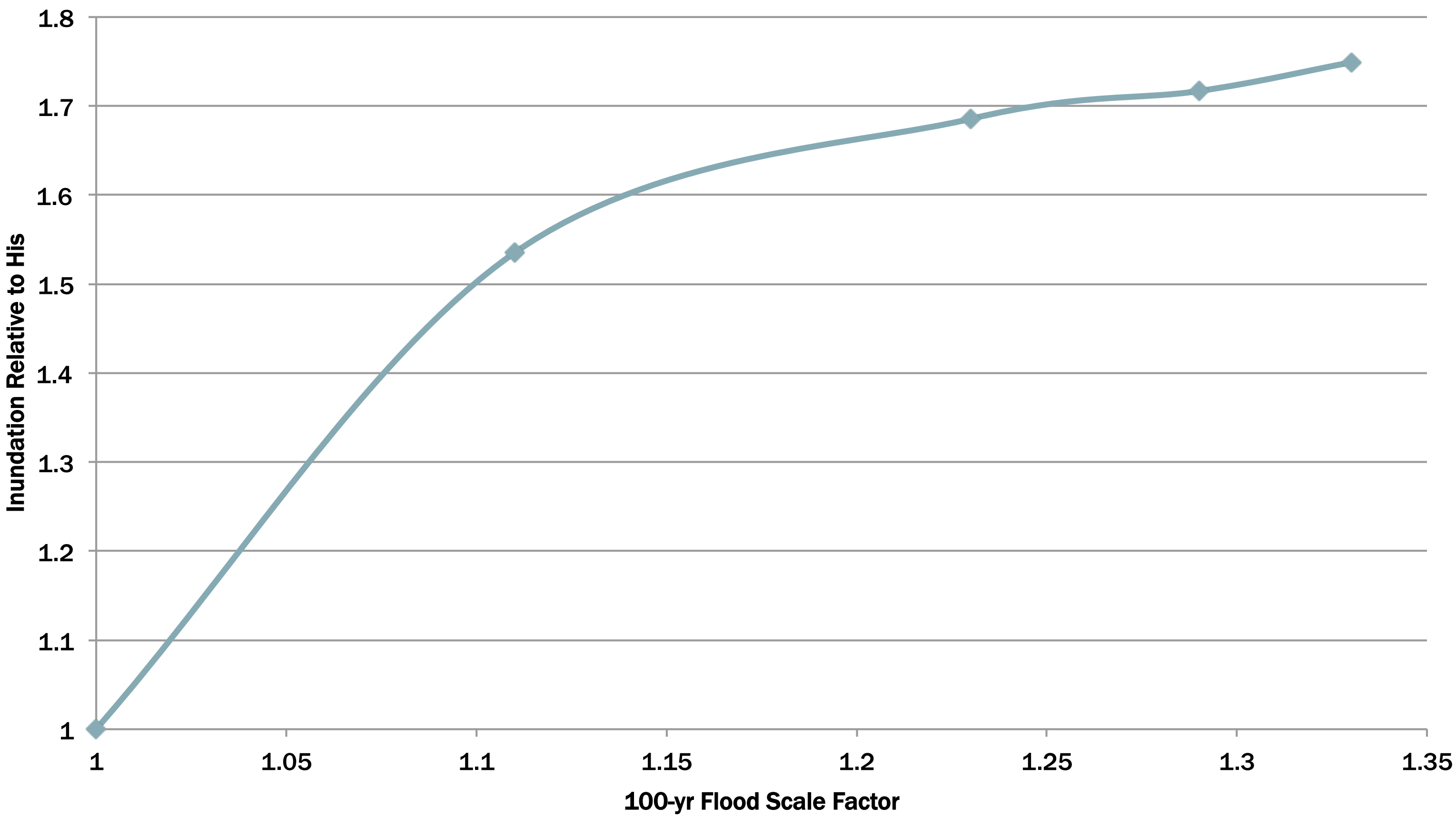
Nisqually River an La Grande



Source: 2860 Project

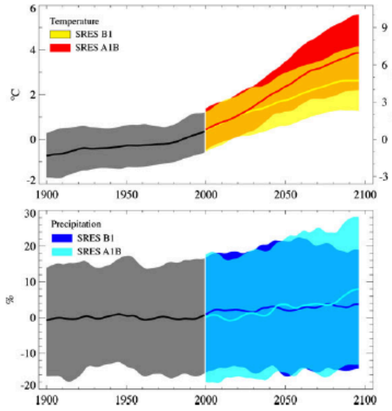
JOINT PROBABILITY OF EXCEEDANCE





1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
Inundation Relative to His
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
100-yr Flood Scale Factor

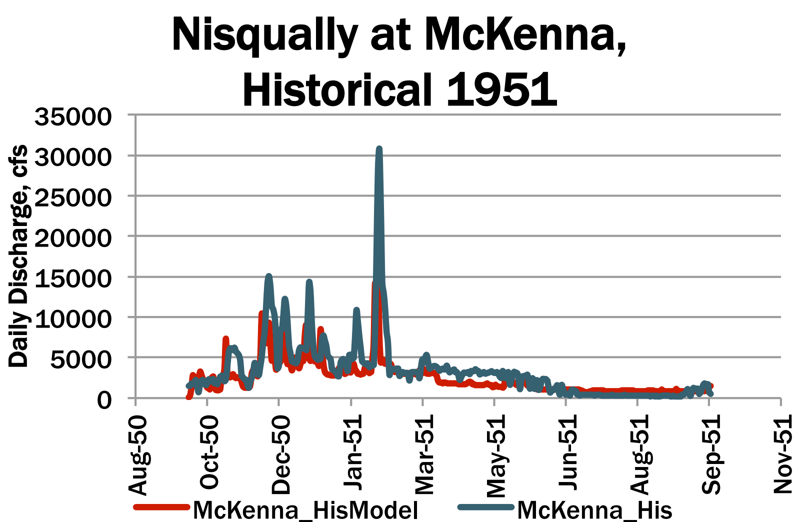
GCM

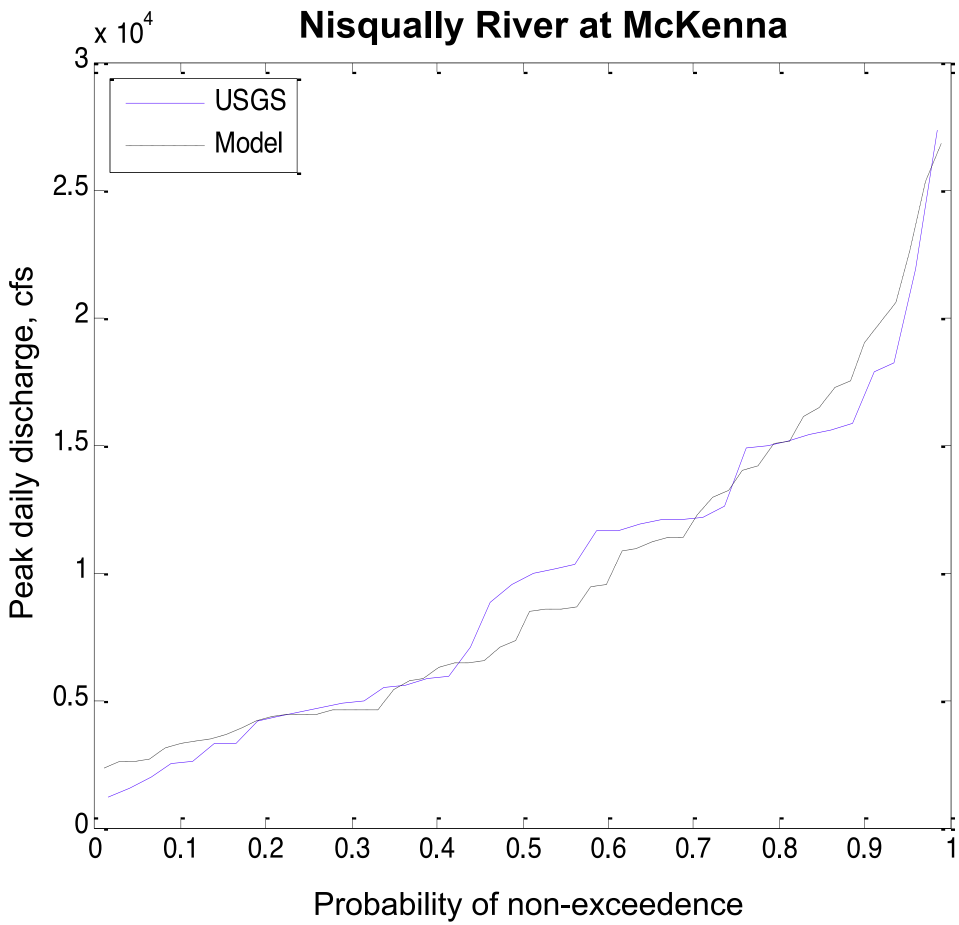


Temperature
SRES B1
SRES A1B
°C
Degrees F
6
4
2
0
-2
9
6
3
0
-3
1900
1950
2000
2050
2100
Precipitation
SRES B1
SRES A1B
%
30
20
10
0
-10
-20
1900
1950
2000
2050
2100

NISQUALLY RESERVOIR MODEL (1)

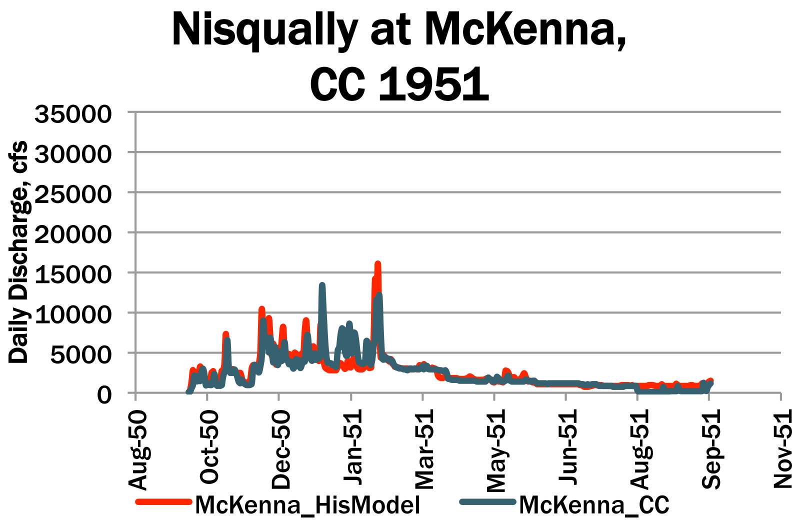
- CDF of peak daily discharge matches that of the gauged record
- Seasonal cycle of operation is captured well
- Individual event statistics are difficult to replicate

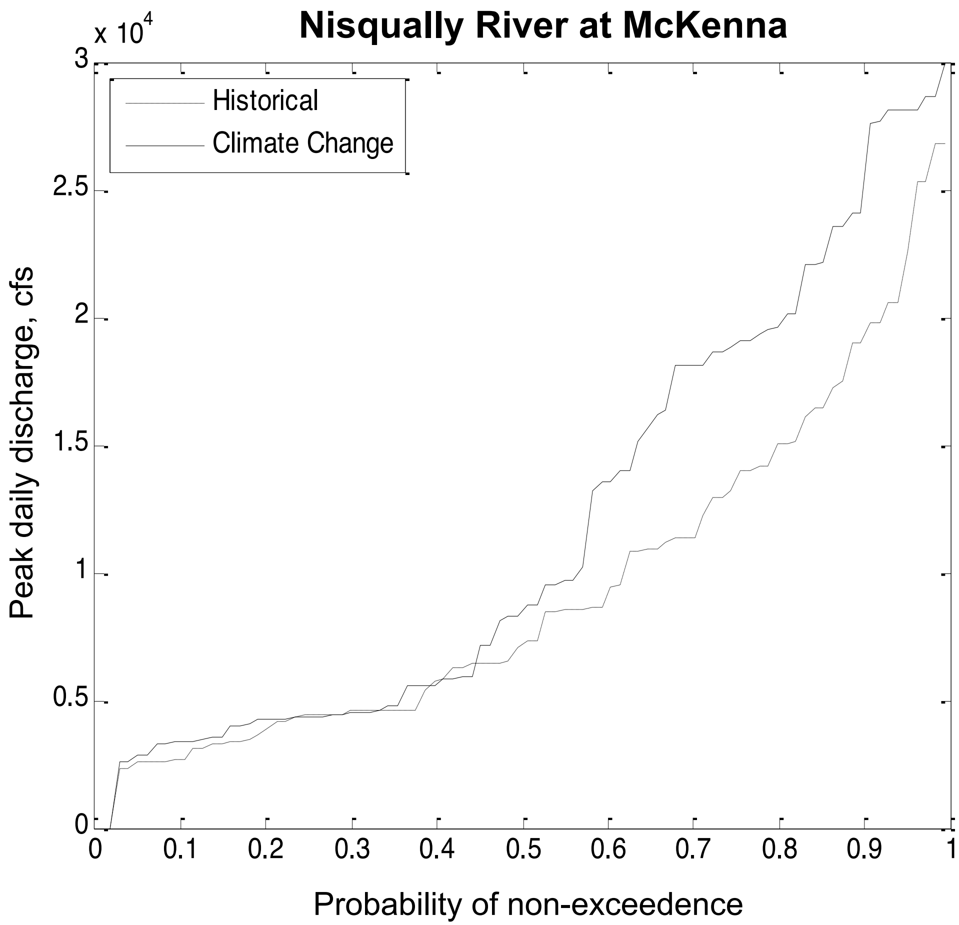


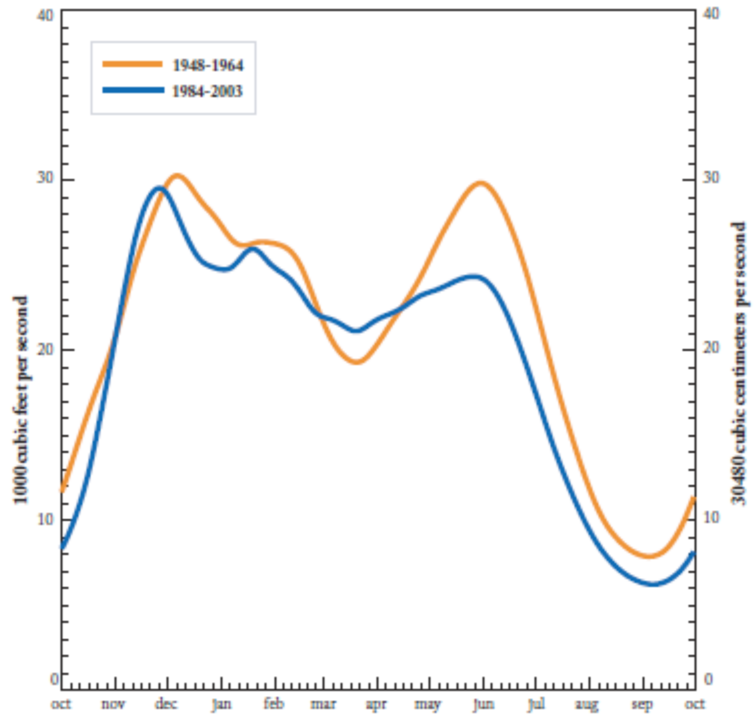


NISQUALLY RESERVOIR MODEL (2)

- Increase of 100-yr storm of approx. 35%

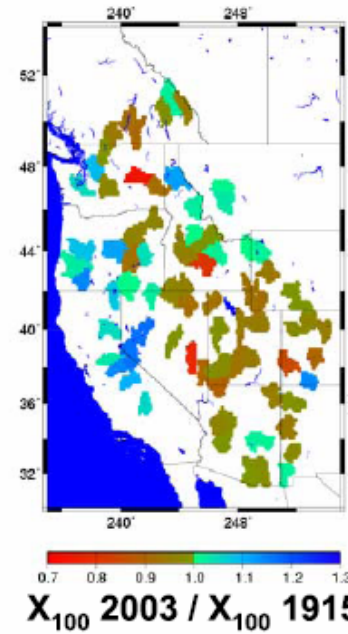


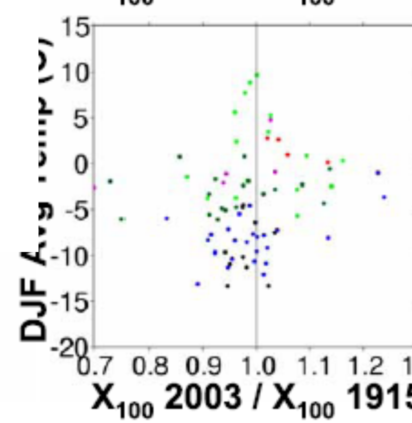


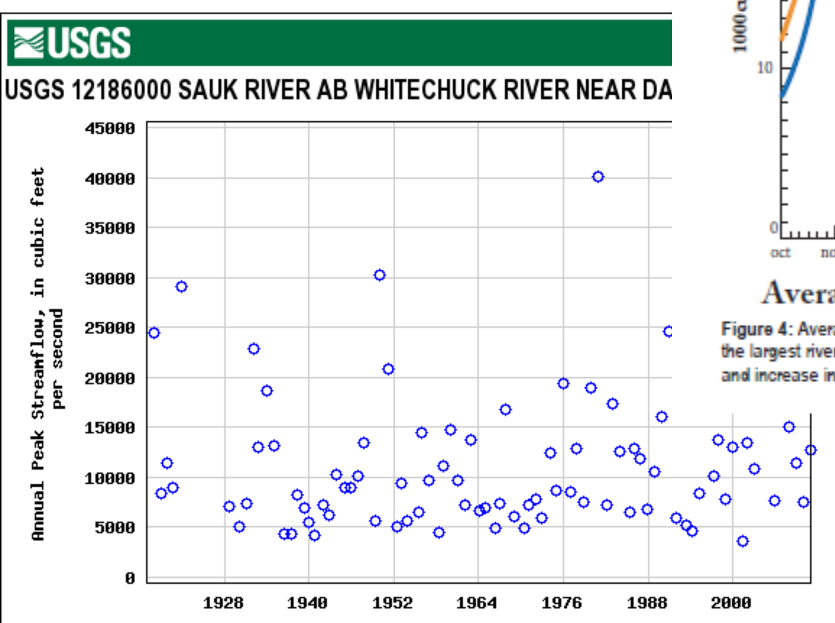


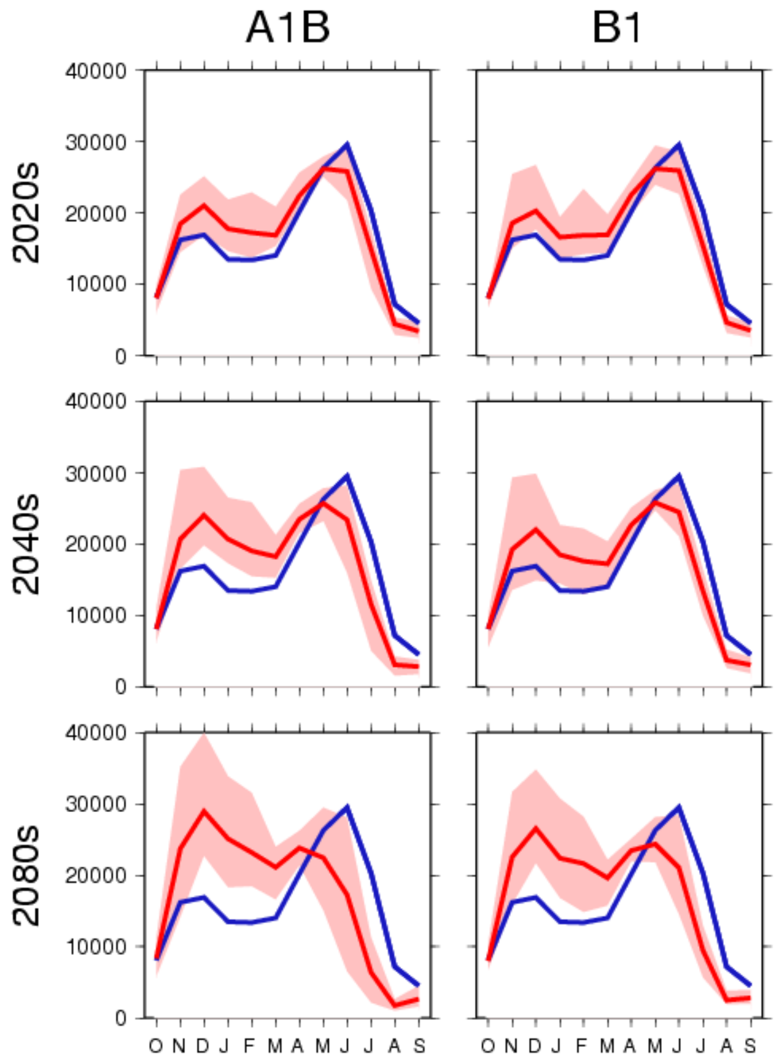
Average Daily Freshwater Flow into Puget Sound

Figure 4: Average daily freshwater flow into Puget Sound (found by adding the flow of nine of the largest rivers) for 1948-1964 (orange) and 1984-2003 (blue). Note the decline in May-October and increase in March-April.









- http://www.atmos.washington.edu/~steed/research/echam5/pcp12.d1.2025-11-29.html
- ← mt vernon

WHAT WE KNOW ABOUT CC IMPACTS

- River Flooding
  - 2860/Elsner results
  - Skagit 2060 results
    - Rule curve changes
- SLR
  - Global SLR
  - Regional SLR
    - Not quite as fast as global rate, may not remain constant

SO WHAT?

- Why do we care about these observed changes in sea level and flooding?

PLANNING FOR FUTURE FLOODING
FLEXIBLE FLOODPLAIN MANAGEMENT

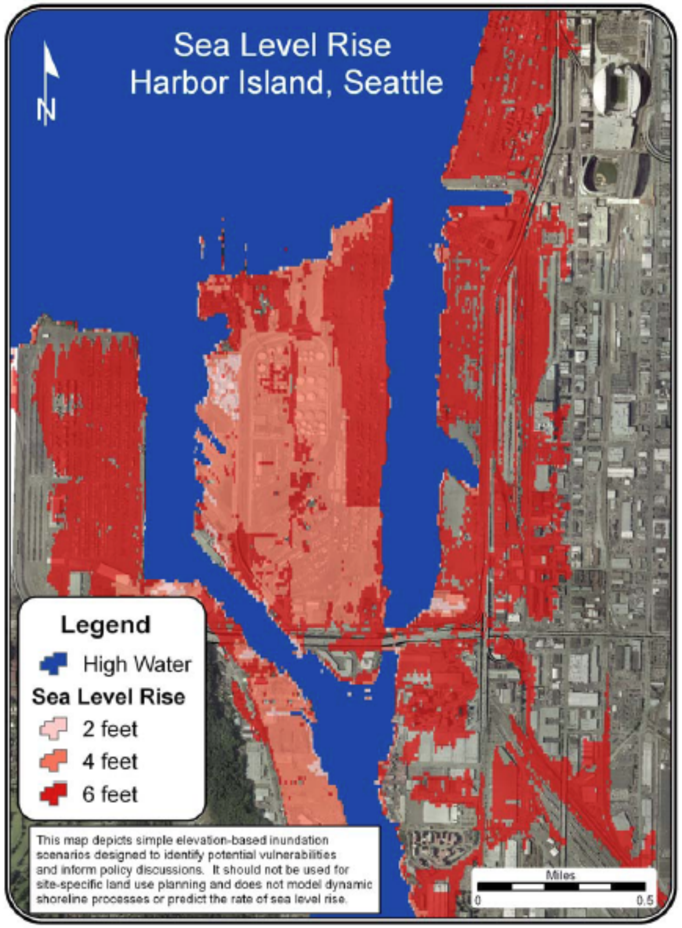
- Move away from reliance on historical record.
- Use scenarios based on projected future conditions.
  - Include changes in climate, sea level, land use, development, etc.
- Think about a range of possible outcomes

DEVELOPING METHODS FOR ESTIMATING FLOOD MAGNITUDES AND EXTENTS

- How can we estimate future flooding in Puget Sound rivers?
- Goal of this project: To quantify flood depths in Puget Sound Rivers based on downscaled climate projections.
- Easier said than done
  - Battling model bias, coarse model output and uncertainty

SEA LEVEL RISE

- Typical estimation of SLR impacts



Source: Peterson, 2007