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Context

- Sub-seasonal to seasonal (S2S) streamflow forecasts represent critical operational inputs for water sectors & society
- S2S hydrological forecast skill is still limited despite advances in many relevant capabilities
- To build a continental-domain forecasting system that has value locally, streamflow predictability should be quantified & communicated

Aims:

- Produce N. America-wide S2S hydrological hindcasts
- Quantify S2S streamflow predictability

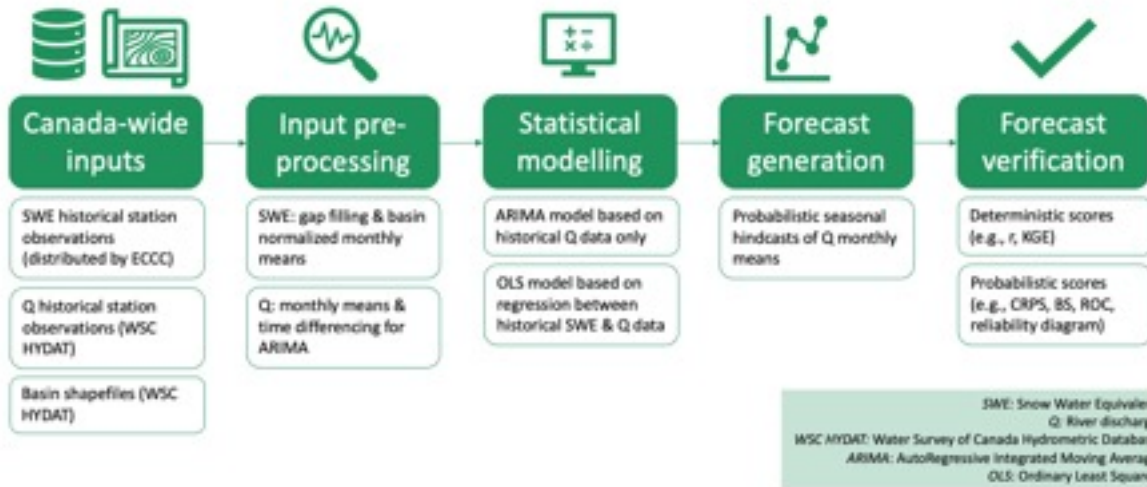


Forecasting workflows

- Two seasonal streamflow forecasting workflows are currently in development

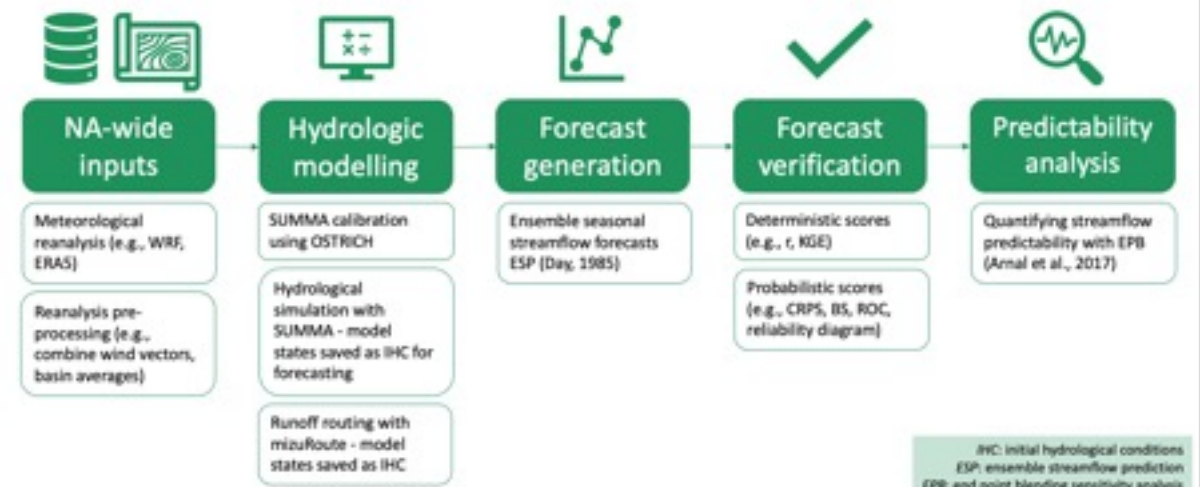
Data-driven workflow

- Benchmark system: can SWE be used for meaningful streamflow predictions across Canada?



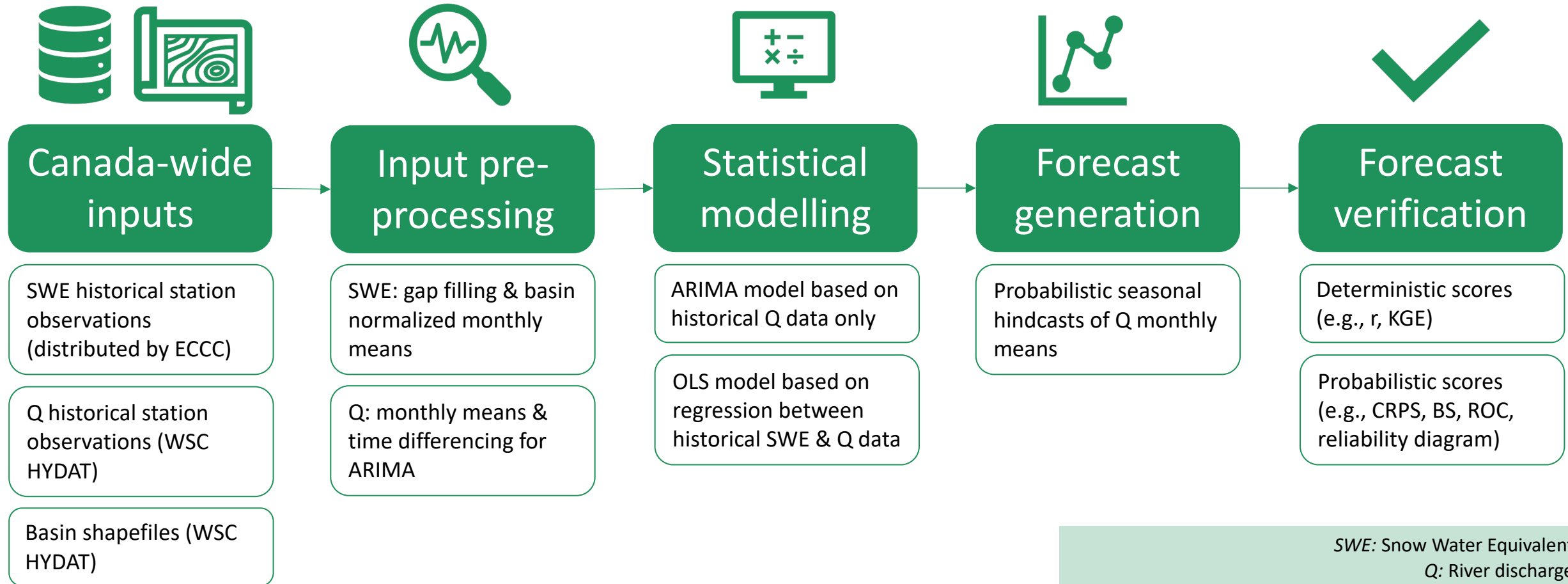
Process-based workflow

- Adapted from the SHARP forecasting system (Andy Wood, NCAR)



Data-driven workflow

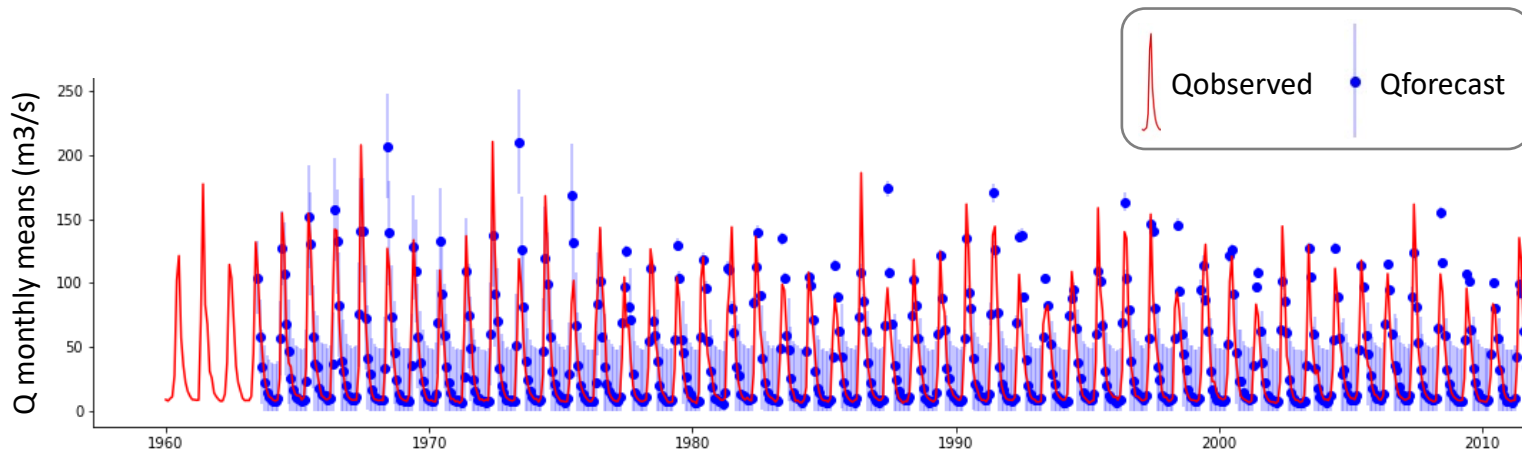
- Benchmark system: can SWE be used for meaningful streamflow predictions across Canada?



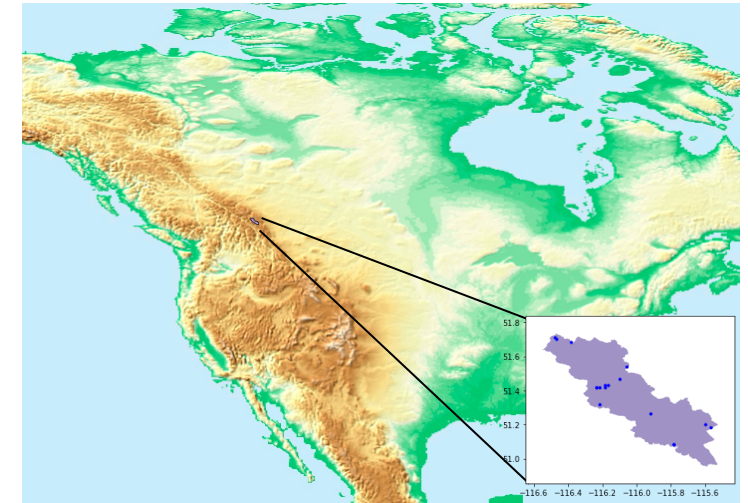
SWE: Snow Water Equivalent
 Q: River discharge
 WSC HYDAT: Water Survey of Canada Hydrometric Database
 ARIMA: AutoRegressive Integrated Moving Average
 OLS: Ordinary Least Squares

Data-driven workflow: Preliminary results

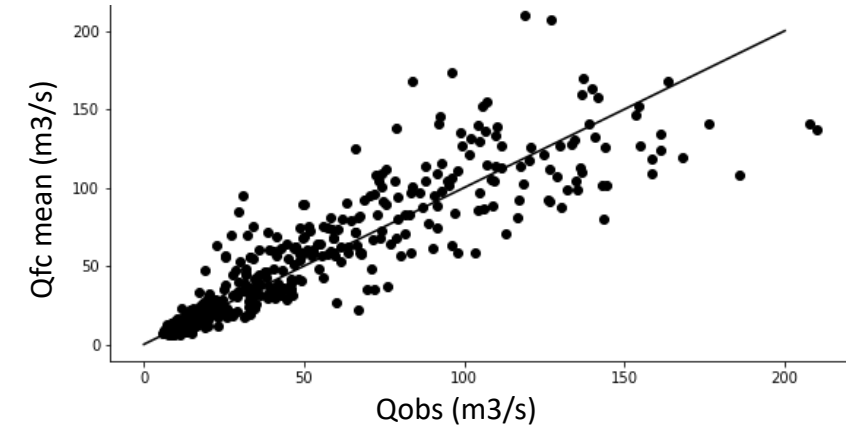
- Merged system: ARIMA for low flow months, OLS for high snowmelt-driven flow months (May-August)
- Merged system allows us to provide hindcasts for:
 - river basins with no SWE data
 - years with no SWE data (e.g., in this case < 1976)
- Overall good agreement between hindcasts & observations



Streamflow monthly mean hindcasts and 95% confidence intervals, using a merged ARIMA-OLS model

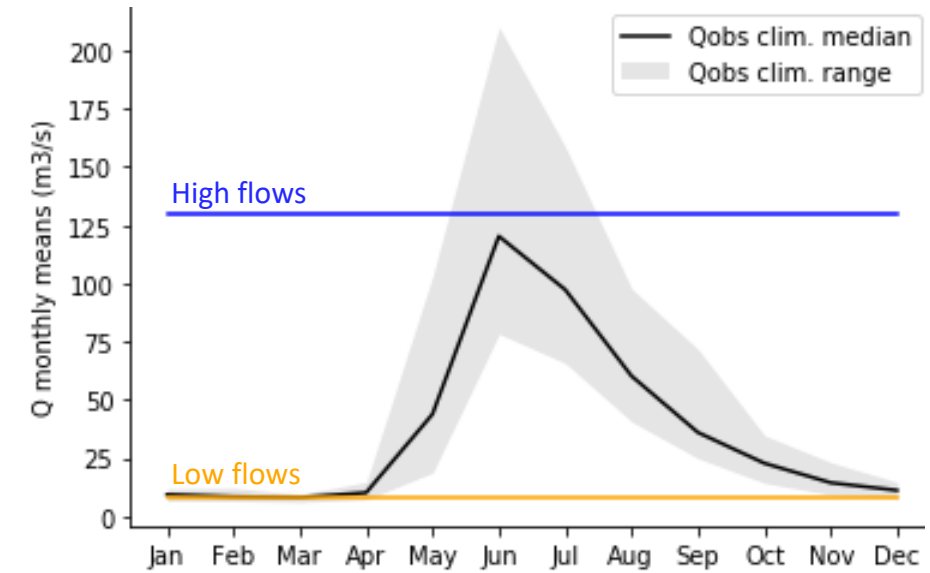
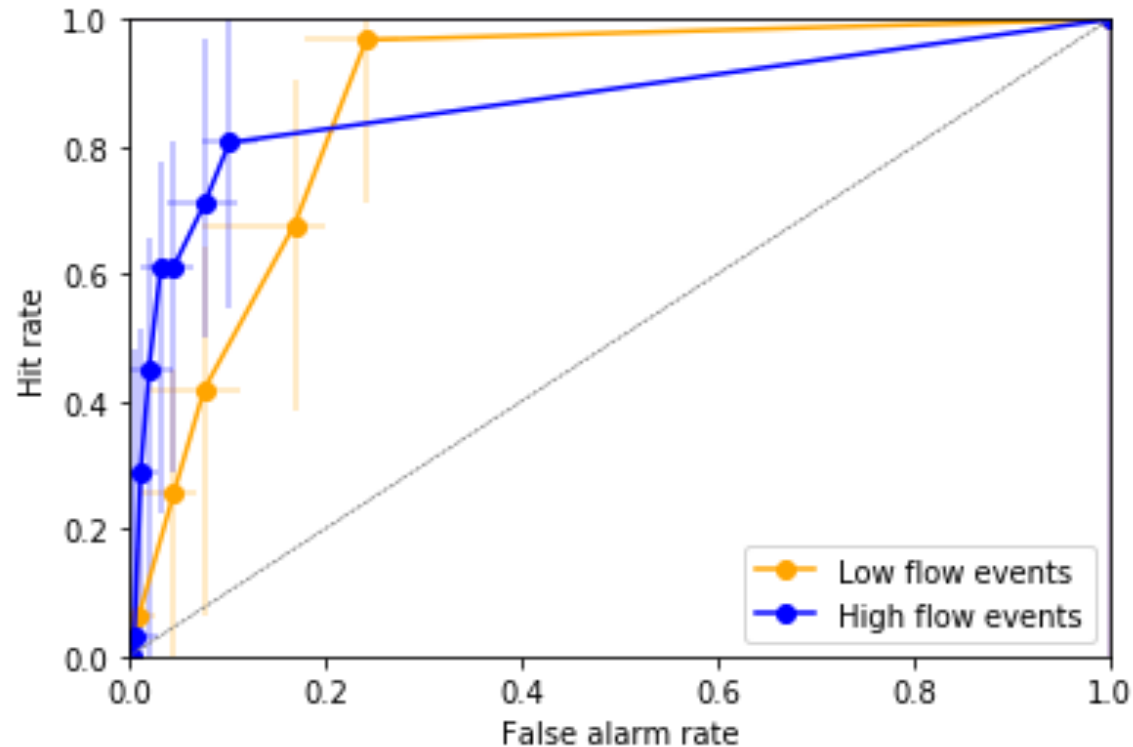


Testbed: Bow at Banff (AB, Canada), with SWE stations (blue dots)



Data-driven workflow: Preliminary results

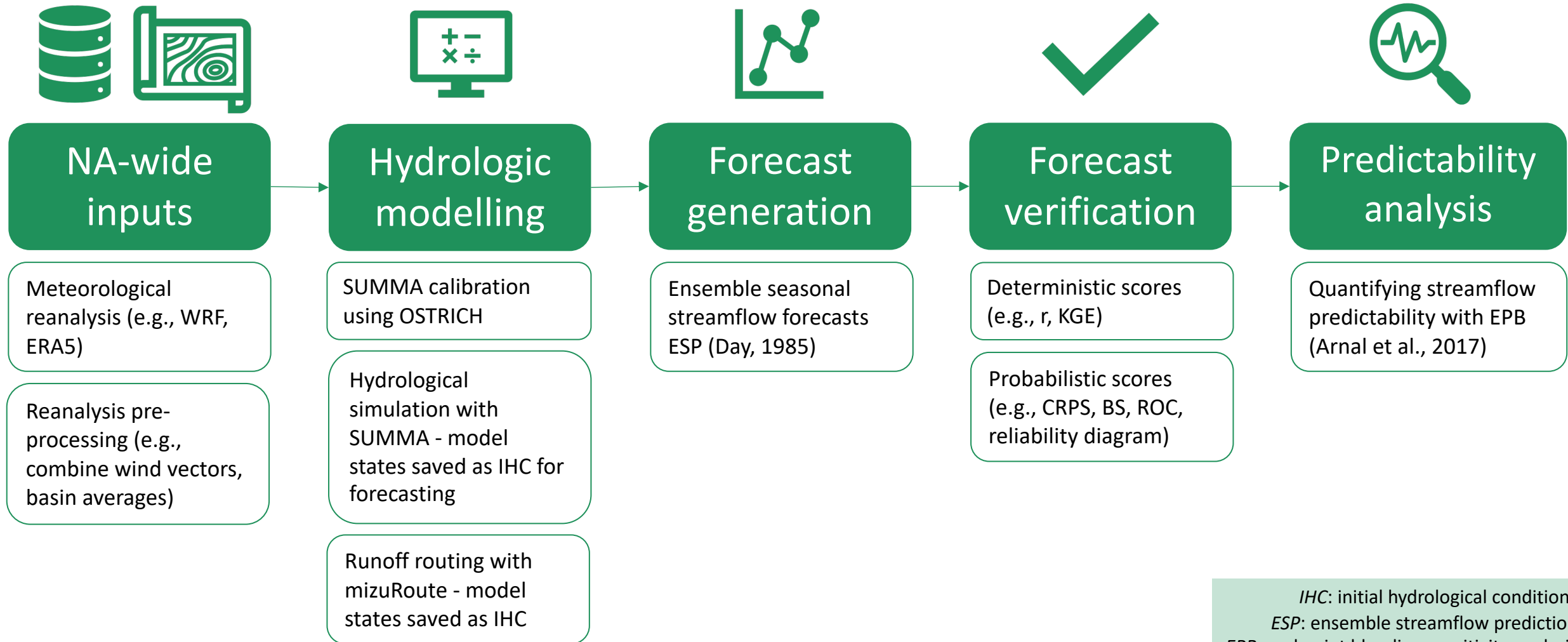
- Preliminary results for the Bow at Banff hint that these hindcasts could be potentially useful for giving an early indication of upcoming high & low flows



ROC curves for low flow events ($Q < 5^{\text{th}}$ perc. of climatology) & high flow events ($Q > 95^{\text{th}}$ perc. of climatology), with bootstrapping intervals

Process-based workflow

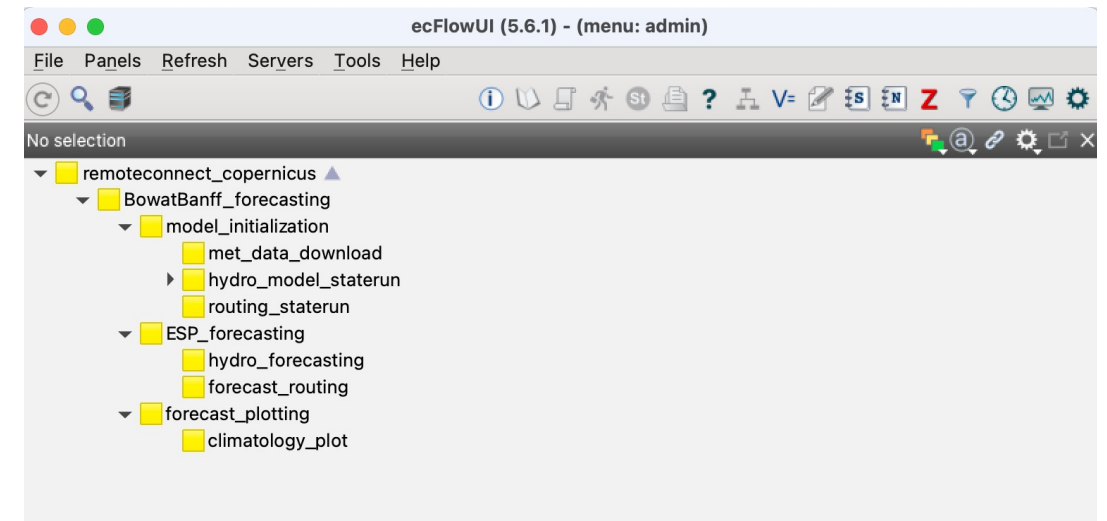
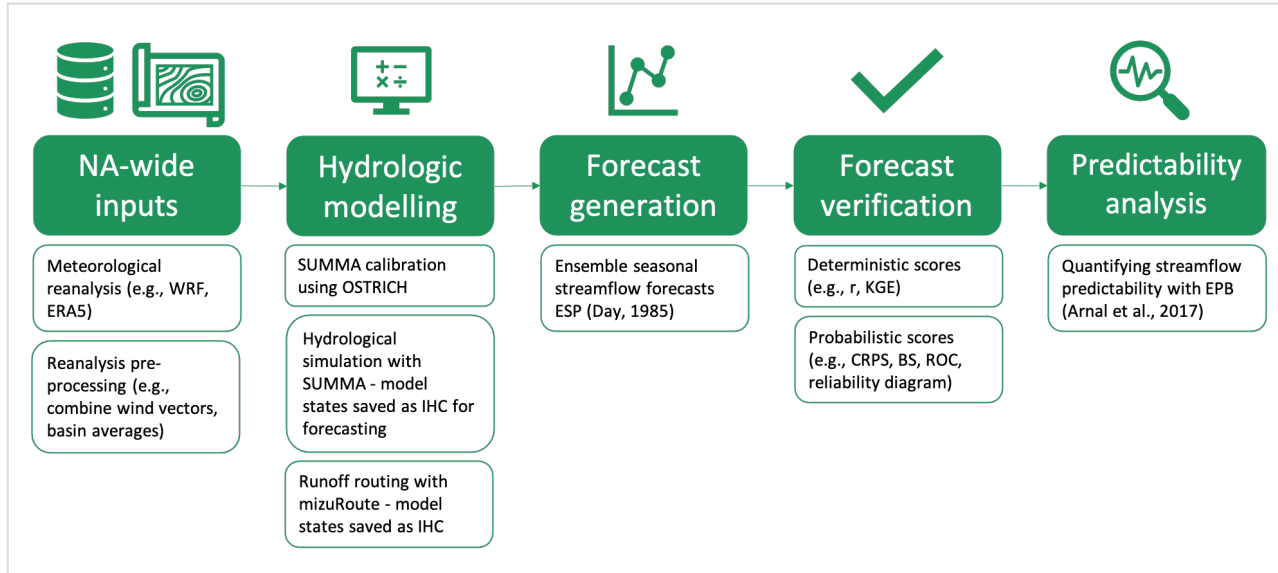
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IHC: initial hydrological conditions
ESP: ensemble streamflow prediction
EPB: end point blending sensitivity analysis

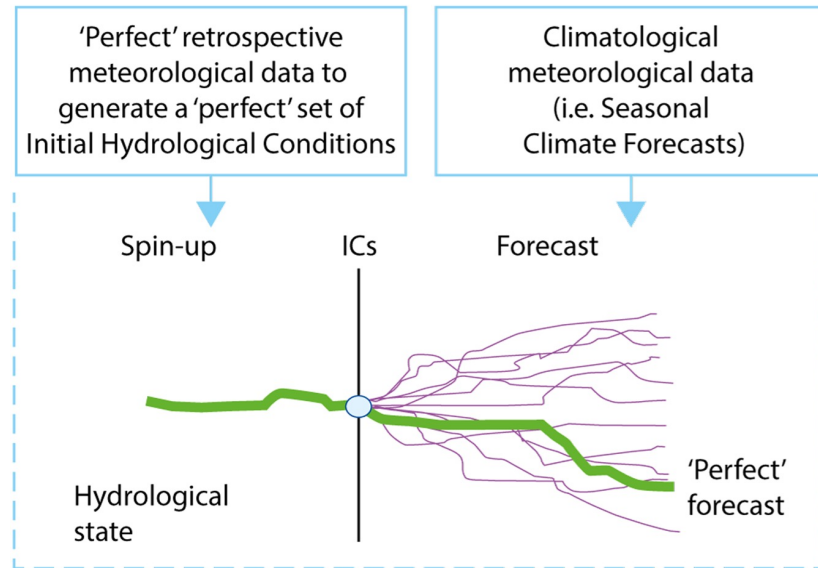
Process-based workflow

- Currently being implemented as a near-real time workflow using ecFlow job scheduler

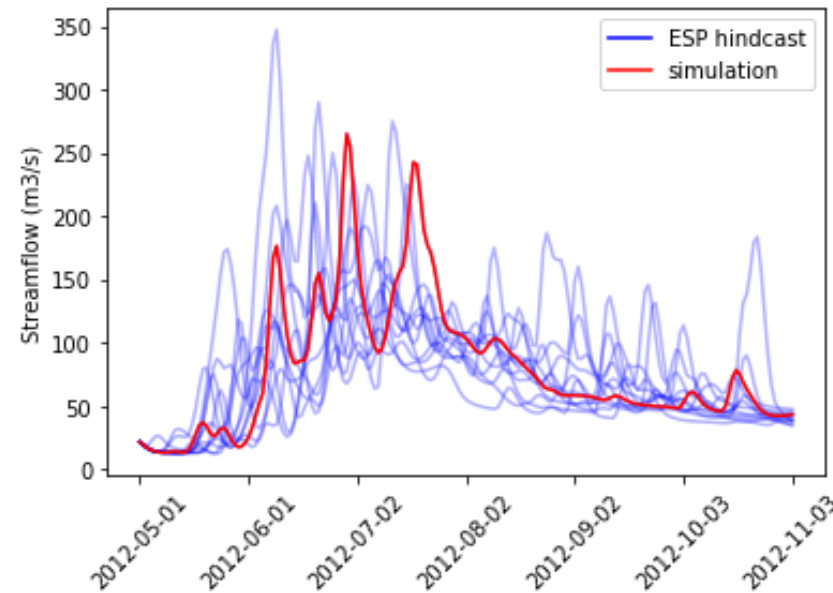


Process-based workflow: Preliminary results

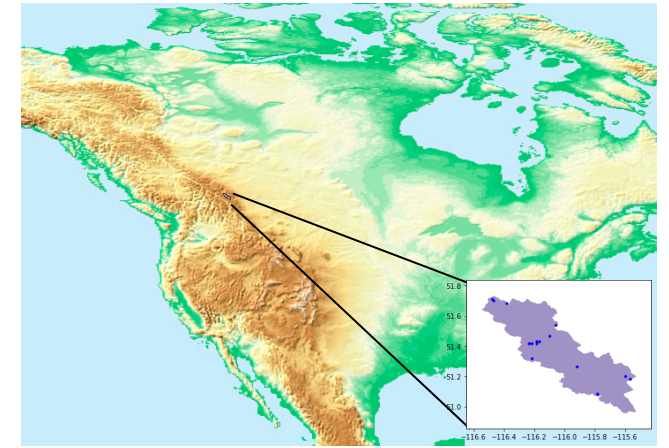
- Preliminary results obtained from WRF reanalysis data
- **ESP hindcasts:** produced from an ensemble of historical met. 'observations' & current IHC (Day, 1985 - J. Water Resour. Plann. Manage.)



Schematic of ESP forecast generation



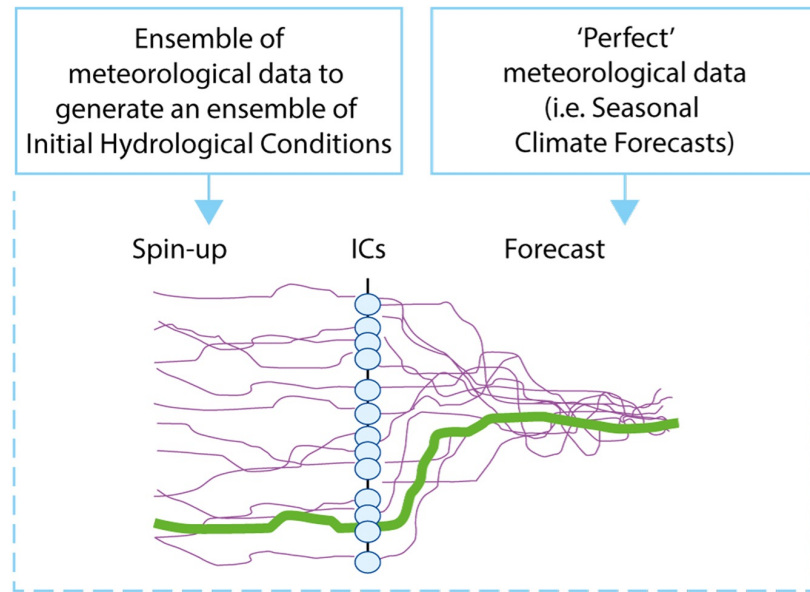
Example ESP ensemble streamflow hindcast (12 ensemble members)



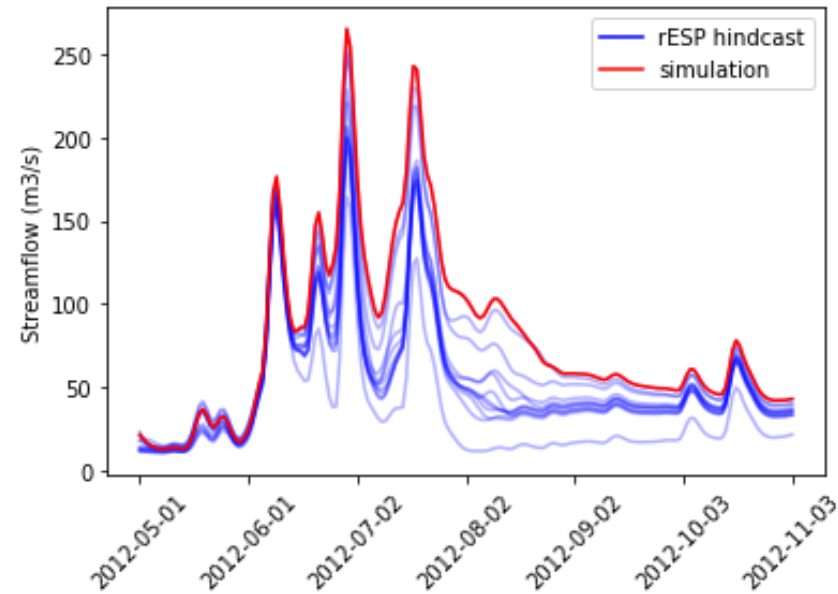
Testbed: Bow at Banff (AB, Canada)

Process-based workflow: Preliminary results

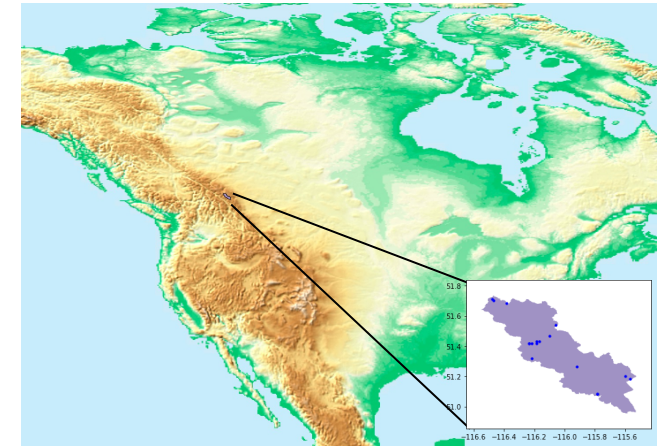
- Preliminary results obtained from WRF reanalysis data
- **Reverse-ESP (rESP) hindcasts:** produced from an ensemble of historical IHC & current met. 'observations' (Wood & Lettenmaier, 2008 - GRL)



Schematic of rESP forecast generation



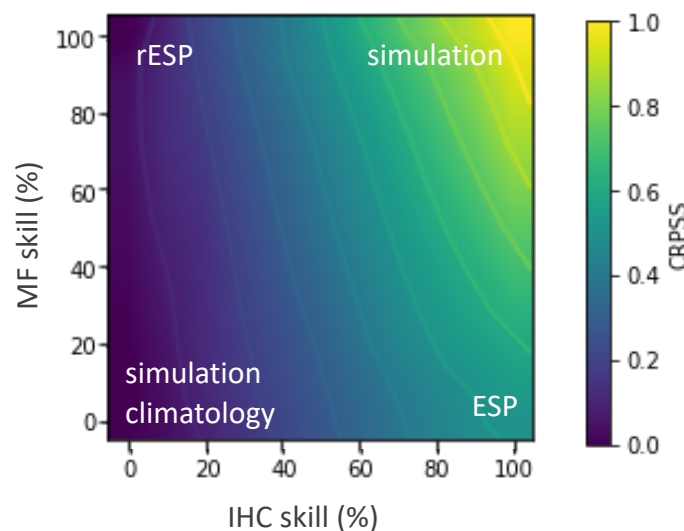
Example rESP ensemble streamflow hindcasts (12 ensemble members)



Testbed: Bow at Banff (AB, Canada)

Process-based workflow: Preliminary results

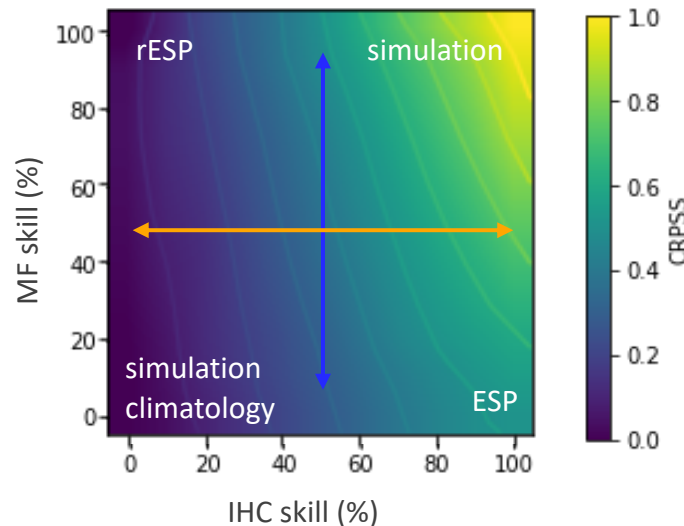
- Predictability analysis:
 - EPB method used to explore the sensitivities of streamflow skill to IHC & met. forcings (MF) errors (Wood et al., 2016 & Arnal et al., 2017 - JoHM)
 - It can help guide resources for tangible seasonal streamflow forecast improvements
- EPB method in a nutshell:
 - New ensemble hindcasts are generated throughout a 2D surface by combining ensemble members from existing datasets (4 end points) with varying weights



Example 2D surface. Each new ensemble hindcast represents a MF-IHC skill combination (0% = climatology to 100% = 'perfect'). The performance of newly generated hindcasts is measured with the CRPSS (baseline: simulation climatology).

Process-based workflow: Preliminary results

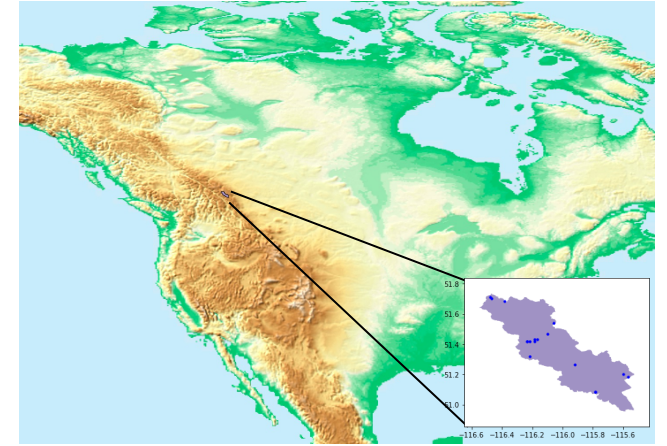
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 - It can help guide resources for tangible seasonal streamflow forecast improvements
- EPB method in a nutshell:
 - New ensemble hindcasts are generated throughout a 2D surface by combining ensemble members from existing datasets (4 end points) with varying weights
 - We can then calculate the streamflow skill elasticities: $E_{IHC} = \frac{Qfc \text{ skill gradient}}{IHC \text{ skill gradient}}$; $E_{MF} = \frac{Qfc \text{ skill gradient}}{MF \text{ skill gradient}}$



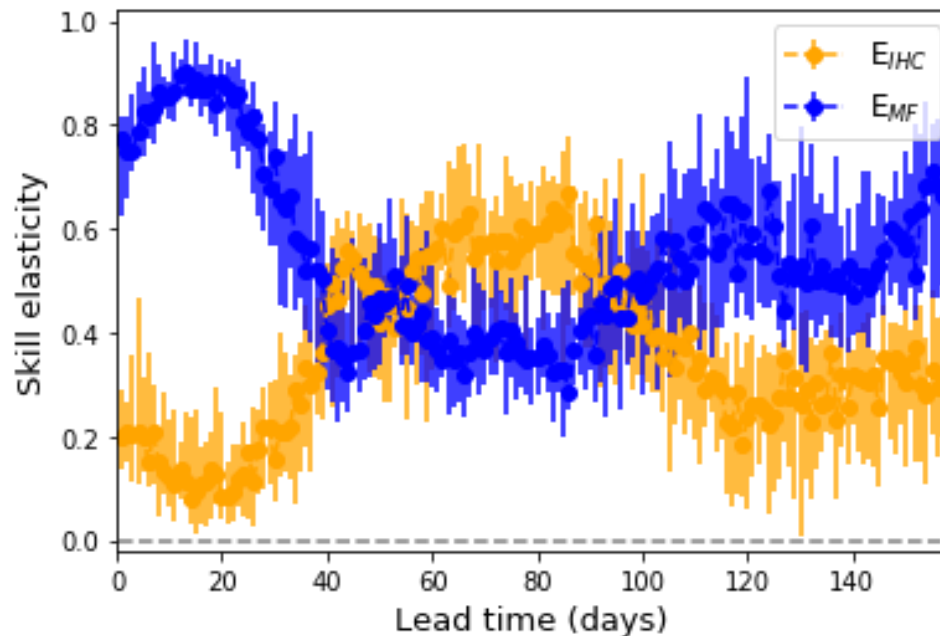
Example 2D surface. Each new ensemble hindcast represents a MF-IHC skill combination (0% = climatology to 100% = 'perfect'). The performance of newly generated hindcasts is measured with the CRPSS (baseline: simulation climatology).

Process-based workflow: Preliminary results

- The skill elasticities are positively oriented:
 - > 0 : expected positive impacts of IHC / MF improvements on streamflow skill
 - $= 0$: no impacts on streamflow skill
 - < 0 : negative impacts on streamflow skill
- Results highlight the variability of streamflow sensitivities depending on lead time & time of year



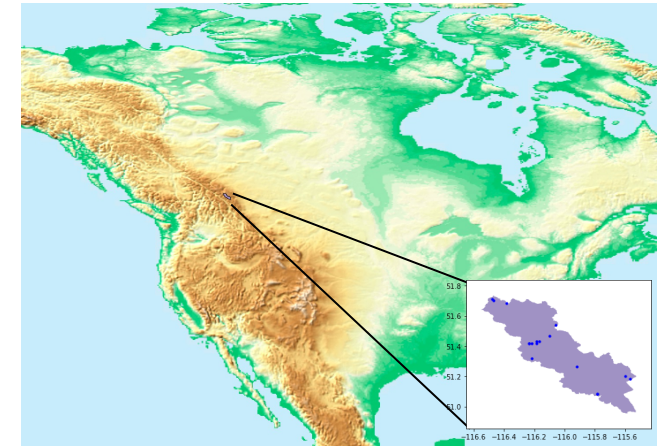
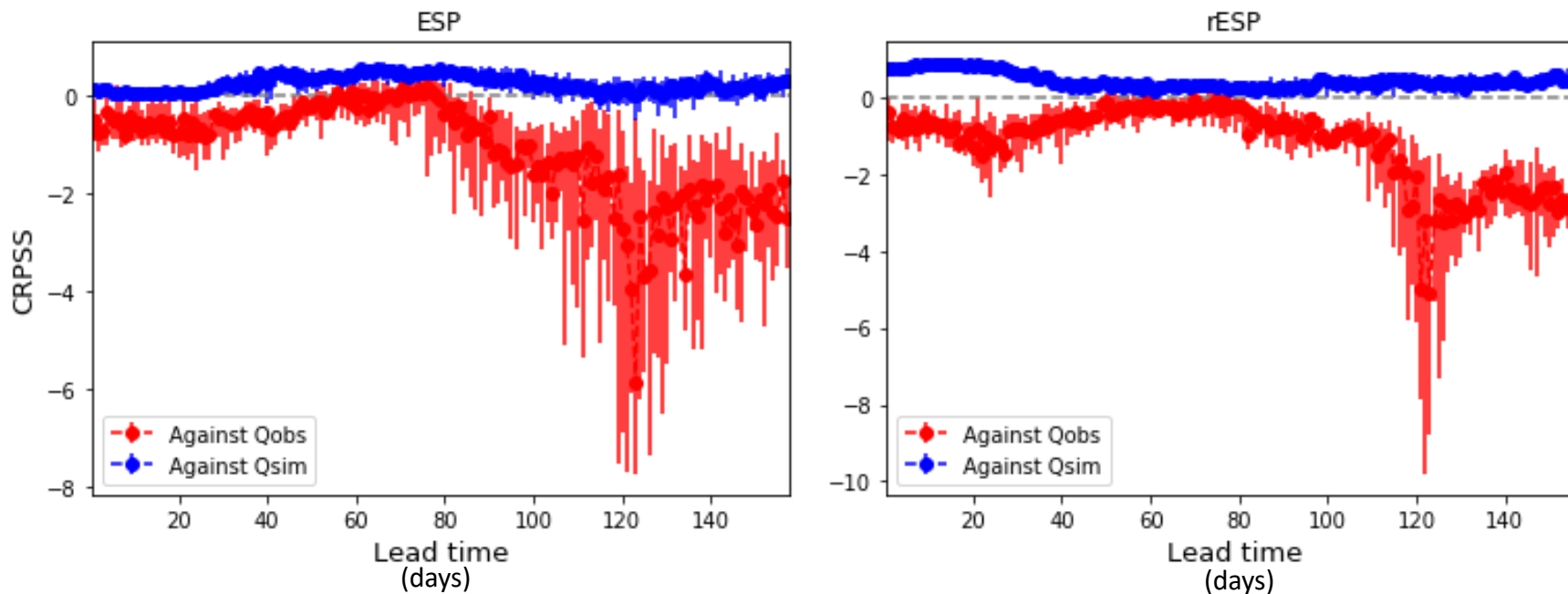
Testbed: Bow at Banff (AB, Canada)



Streamflow skill elasticities to the IHC (E_{IHC}) & MF (E_{MF}), with 90% confidence intervals from bootstrapping. Obtained from 12 years of hindcasts with a 1st May start and up to 187 days lead time. The hindcasts' skill was assessed with the CRPSS (baseline: simulation climatology)

Process-based workflow: Preliminary results

- But we shouldn't forget that this is all in the modelled world
- In the real world the picture is more complicated
- EPB results might look different if we account for model uncertainties



Testbed: Bow at Banff (AB, Canada)

ESP and rESP streamflow hindcast skill (CRPSS) against Qobs & Qsim, with 90% confidence intervals from bootstrapping. Obtained from 12 years of hindcasts with a 1st May start and up to 187 days lead time.

Take-Home

- To build a continental-domain forecasting system that has value locally, we are:
 - developing two streamflow forecasting workflows (data-driven & process-based) for North America
 - quantifying S2S streamflow predictability for basins across North America
- Future work will include upscaling these testbed workflows to North America

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