CMIP6 streamflow benchmarking over the Arctic

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ABSTRACT

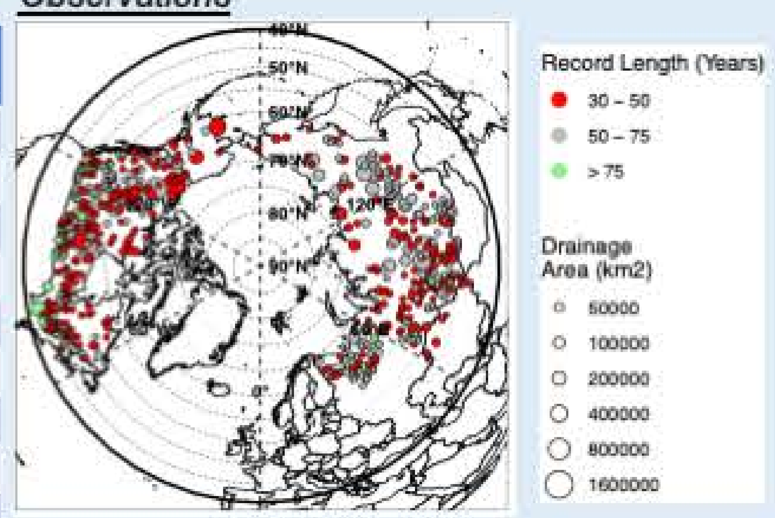
Earth System Models (ESMs) included in the Coupled-Model-Intercomparison Project (CMIP) are considered sophisticated in their ability to project the impacts of future climate on important hydroclimatic variables and Earth system processes. However, little is known about their performance against observations across standard hydrological metrics, which hampers our ability to understand their actual utility for simulations under a changing climate, particularly for high-latitude environments due to Arctic amplification. We assess the performance of simulated Arctic runoff that has been routed to river channels using a physically based river routing model, Model for Scale Adaptive River Transport (MOSART), from eleven CMIP6 models. Models were evaluated using metrics to assess model skill for representing total volume, variability, seasonality, extreme events, and overall distributions, which are evaluated over multiple timescales (e.g. daily, monthly, and annual) across the Pan Arctic. Data are compared to observations from medium-to-large river basins (>10,000 km2, n = 611 gages), as the coarse resolution of ESMs prohibits comparison for smaller river basins. Our results indicate that while one-to-one comparisons between ESMs and observations usually result in poor performance, particularly at the daily scale, the ESMs demonstrate some skill in prediction at coarser timesteps or when techniques such as statistical averaging and best-fit model selection were used. We are also able to highlight some spatial structure in the performance of the models for the different metrics. This work is anticipated to be highly useful for understanding the most appropriate applications for ESM streamflow when attempting to understand how Arctic hydrology will change under a future climate.

METHODS

Models

CMIP6 Models	Origin	Land Model Component	Resolution (degree)
BCC	China	BCC-AVIM	1.125
CanESM5	Canada	CLASS-CTEM	2.8125
CESM2	U.S.	CLM	1
EC-Earth4	E.U.	HTESSEL	0.7
E3SMv2	U.S.	ELM	1
GFDL-ESM4	U.S.	LaD Model	1
IPSL-CM6a-LR	France	ORCHIDEE	2
MIROC6	Japan	MATSIRO	1.4
MPI-ESM	Germany	JSBACH	0.9375
MRI-ESM2-0	Japan	AGCM	1.125
Nor-ESM2-LM	Norway	CLM	2

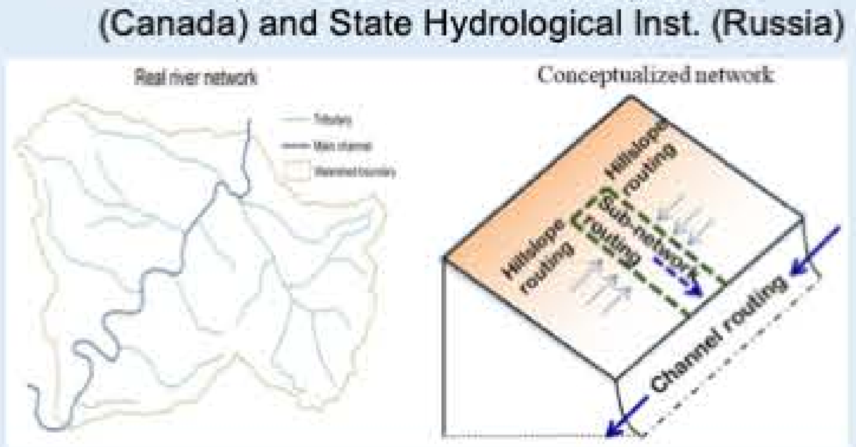
Observations



- 611 gages where basin size > 10,000 km^2
- Daily, monthly, annual (1920-2014)
- Ownership: US Geological Survey, Hydat (Canada) and State Hydrological Inst. (Russia)

Model for Scale Adaptive River Transport

- Takes in 0.5-deg runoff from CMIP6
- Divides water into hillslope runoff, surface/subsurface tributaries, channel flow
- No exchange between land and atmosphere



Observations

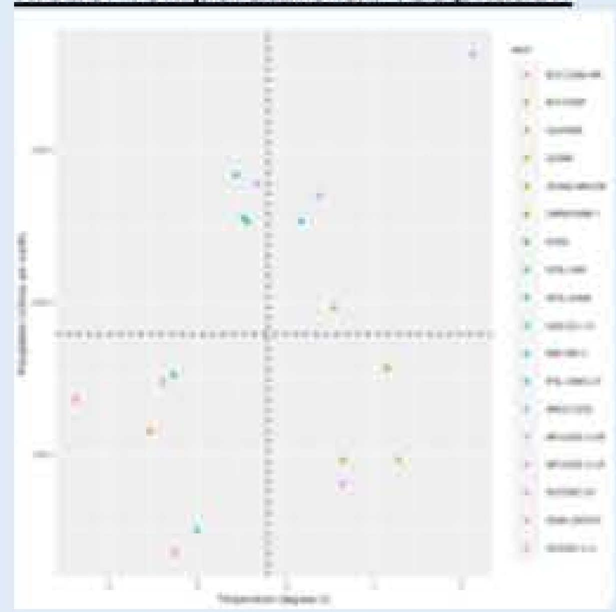
CMIP6 Models	Agency Ownership	Number of Records	Mean Record Length (yr)	Range Record Length (yr)	Mean Basin Size (km^2)
Daily	USGS	8	50.6	36.7 – 70.0	231,920
Daily	Hydat	152	60.8	36.0 – 159.0	127,181
Daily	SHI	21	57.2	37.8 – 74.0	28,491
Monthly	USGS	8	50.6	36.7 – 70.0	231,920
Monthly	Hydat	152	60.8	36.0 – 159.0	127,181
Monthly	SHI	159	58.0	36.2 – 117.8	169,817
Annual	USGS	8	50.6	36.0 – 159.0	231,920
Annual	Hydat	152	60.8	36.7 – 70.0	127,181
Annual	SHI	159	58.0	36.2 – 117.8	169,817

Metrics

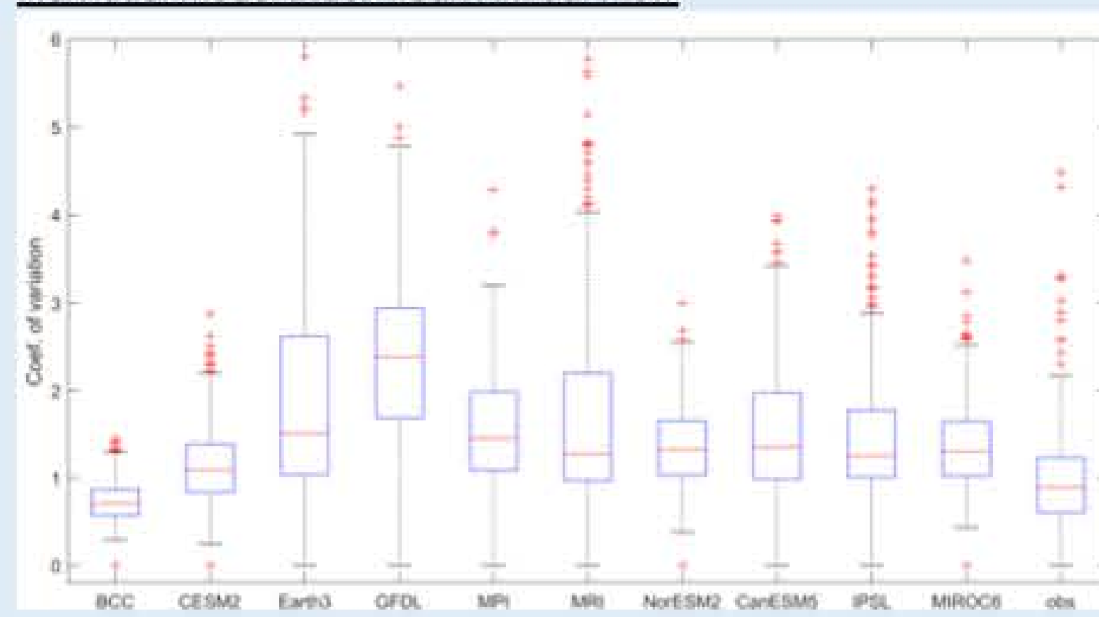
Metric	Abbreviation	Temporal Resolution	Description
Pearson Correlation Coefficient	PCC	Daily, Monthly, Anuual	Ratio between the covariance of model and observation and the product of their standard deviations
Normalized Root Mean Square Error	nRMSE	Daily, Monthly, Anuual	The standard deviation of residuals (difference between model and observation)
Nash Sutcliffe Efficiency	NSE	Daily, Monthly, Anuual	One minus the ratio of error variance of the modeled time series divided by the variance of the observed time series
Center Timing	CT	Daily	The Julian Day in which half the volume of streamflow has passed through a given point
7-day mean low flow	7Q10	Daily	The lowest mean 7-day flow that occurs once every 10-years
100-year return period high flow	Q100	Daily	The peak flow that occurs once every 100-years
Mean Annual Flow	MAF	Daily, Monthly	The mean annual flow occurring over a given period
Seasonality Index	SI	Monthly	The level of seasonal variation in streamflow: values vary from 1, where streamflow volume spread uniformly across all months; to 12, where all streamflow volume is concentrated in single month
Peak Flow Month	PFM	Monthly	Month when peak monthly flow occurs

RESULTS AND DISCUSSION

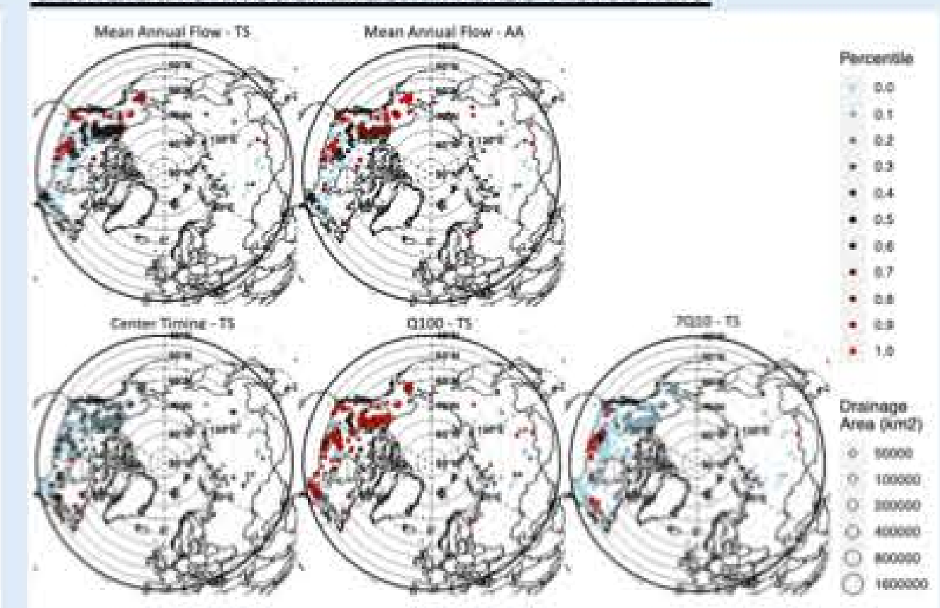
Model Temperature & Precipitation



Individual Model Bias: Mean Annual Flow

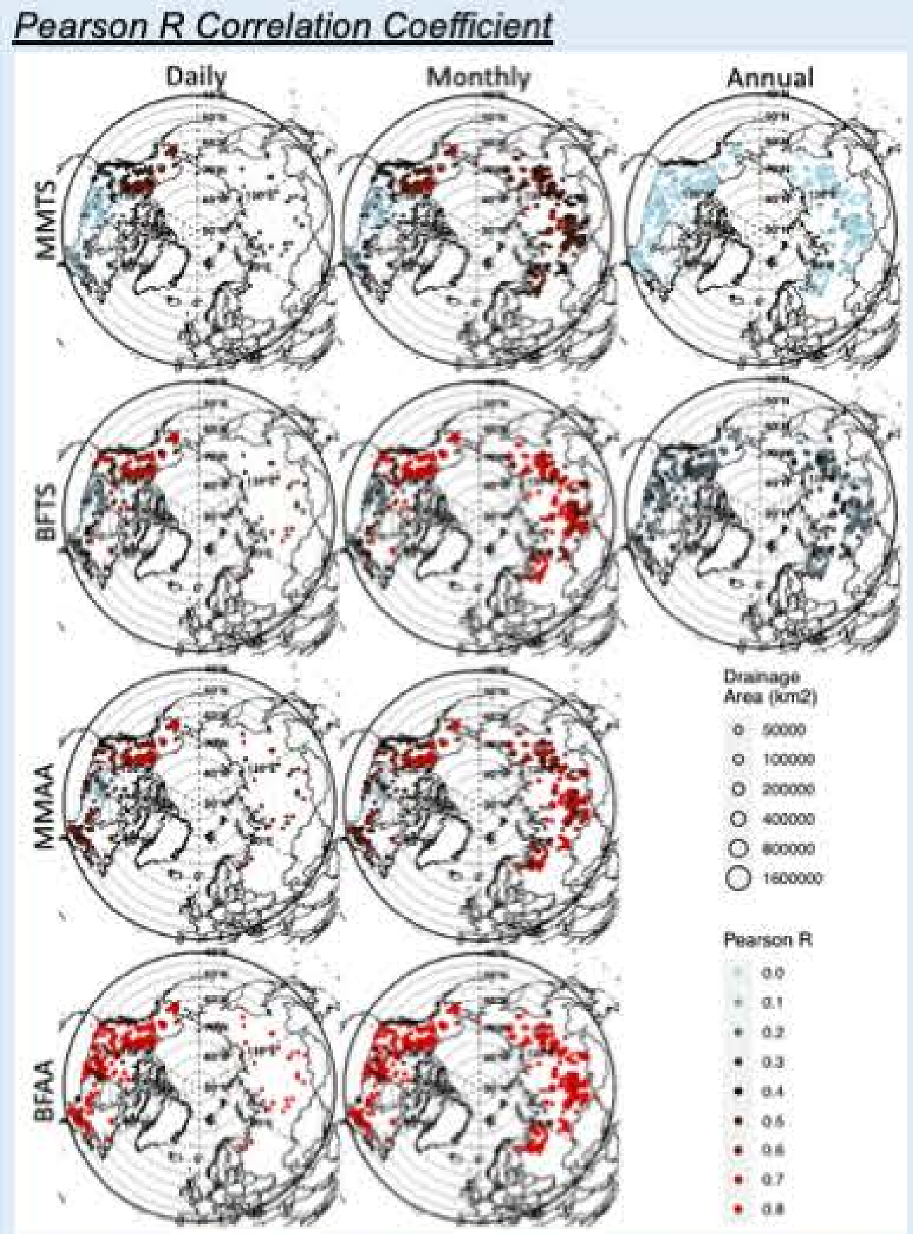


Cumulative Model Bias: Inverse Percentile

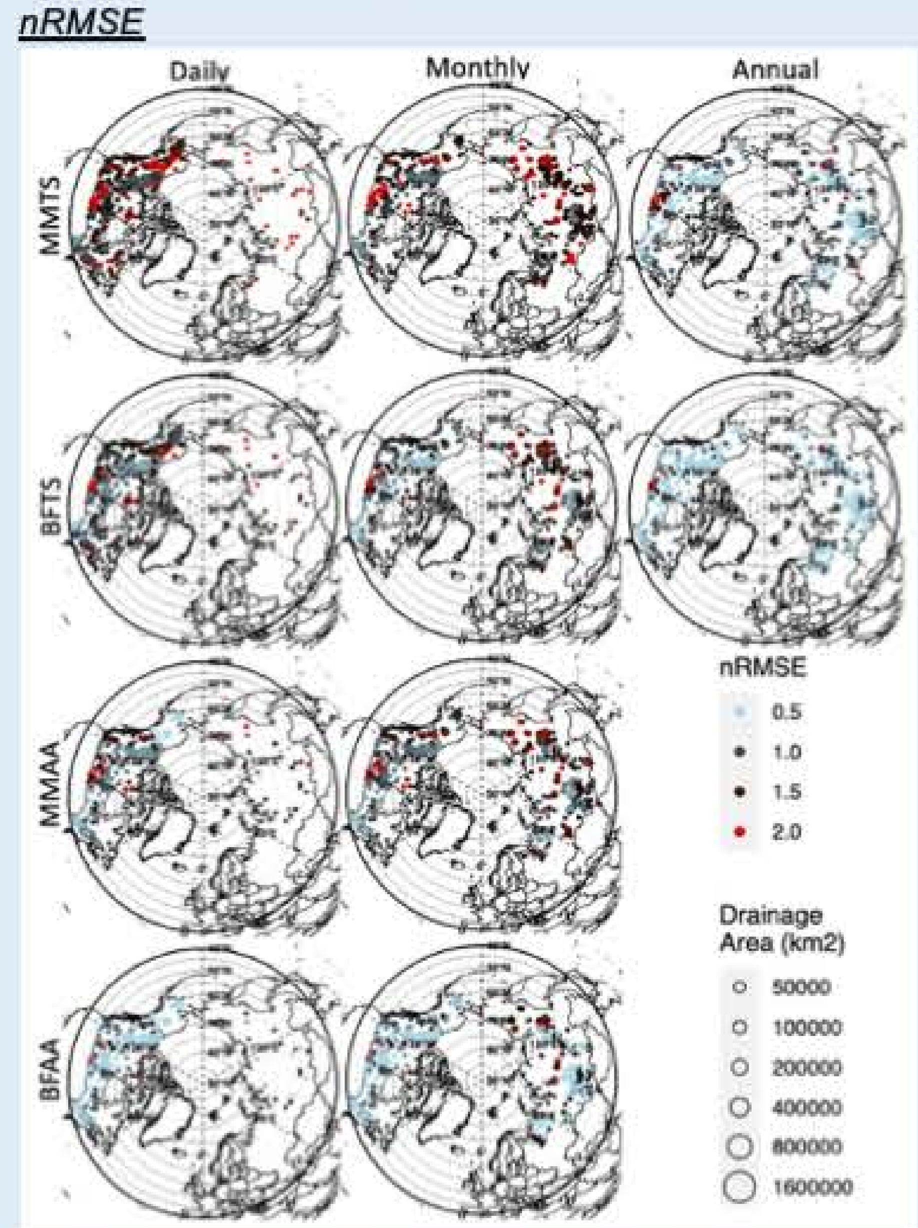


- Precipitation-Temperature biases for CMIP6 models indicate fairly equal representation across four quadrants
- CMIP6 models tend to be biased low relative to observations with noticeably higher variability in Earth3, GFDL, MRI and CanESM5; lower in BCC
- High biases tended to persist through individual metrics mean annual flow and Q100 high flows, although 7Q10 low flow and center timing biased low for most models

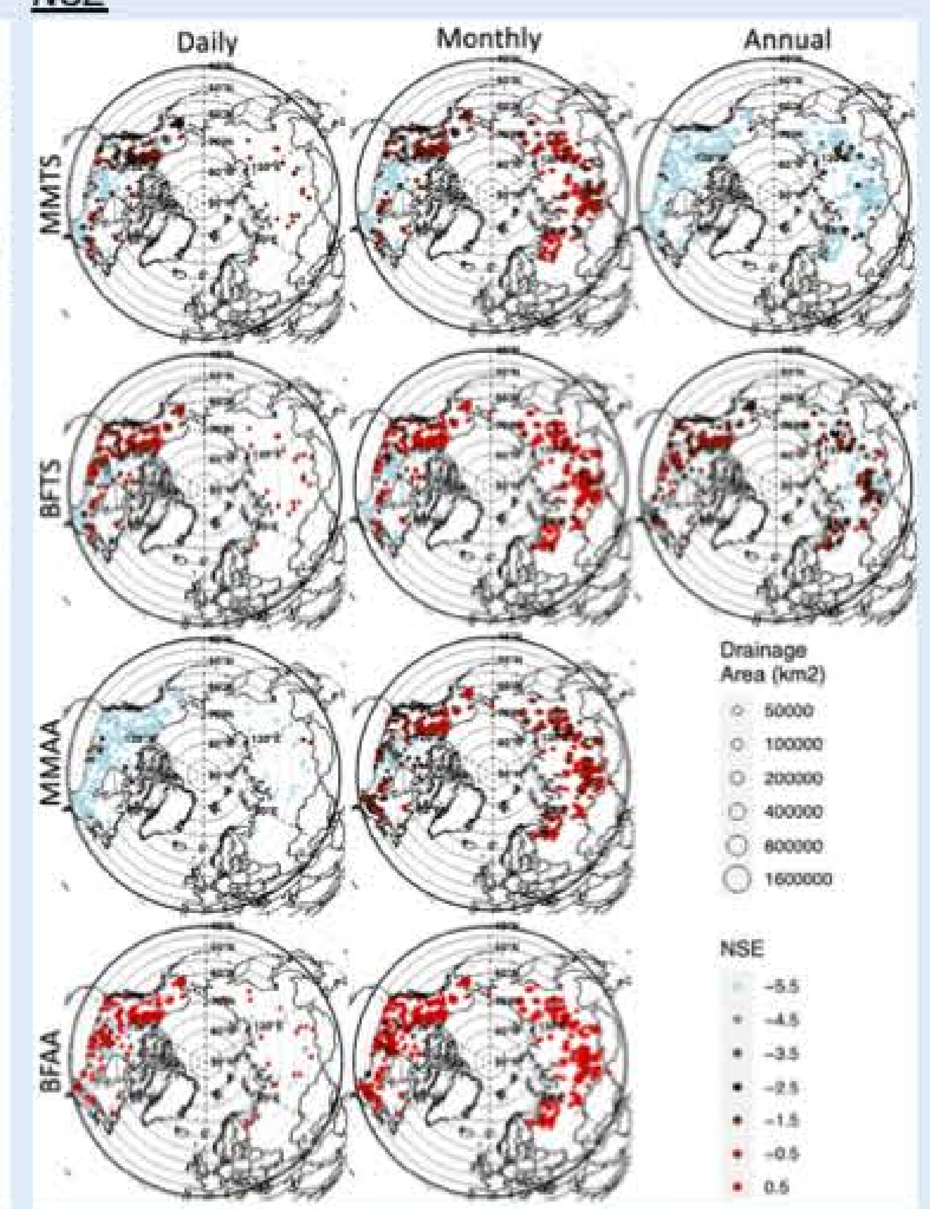
Pearson R Correlation Coefficient

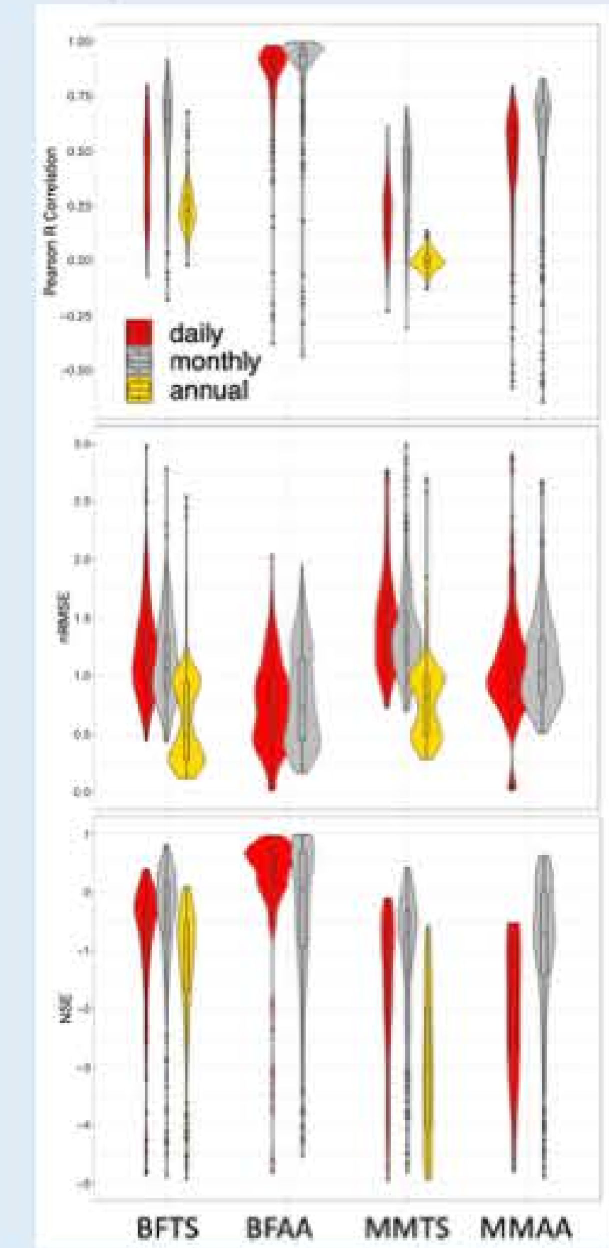


nRMSE



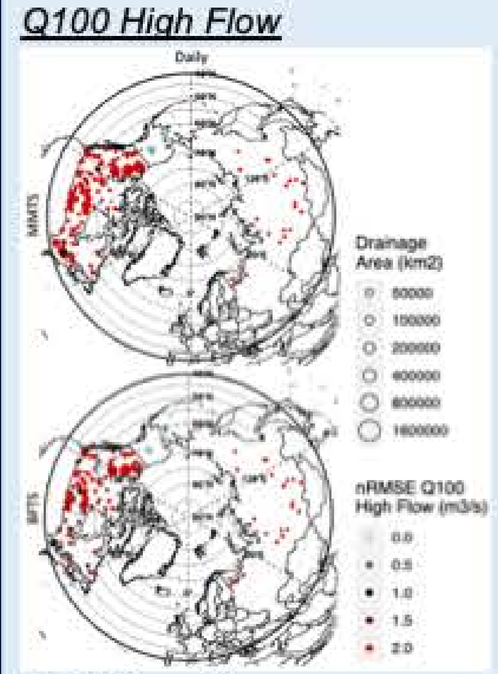
NSE



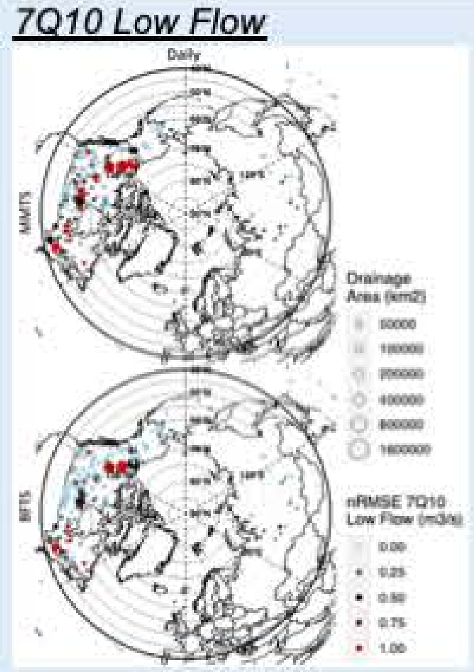


- Note: MMTS = multi-model mean time series, BFTS = best-fit model time series, MMAA = multi-model mean annual average, BFAA = best-fit model annual average comparisons
- Model performance generally poor at daily timestep with some regional exceptions except when BFAA technique is used; general model improvement at monthly timestep
- Annual timestep and interior Canada sees lower performance for capturing variability (PCC & NSE) but better at capturing model bias (nRMSE)

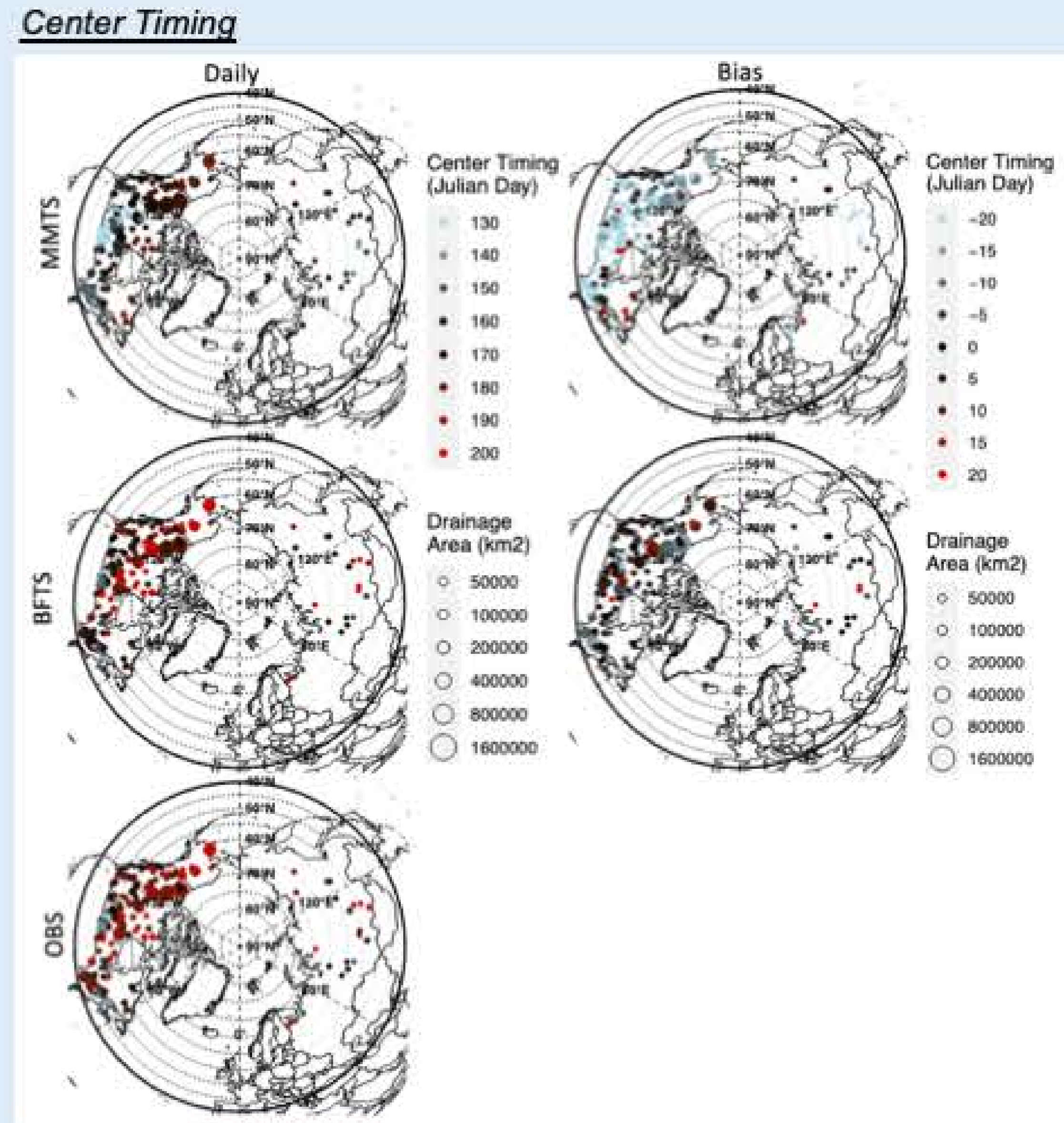
Q100 High Flow



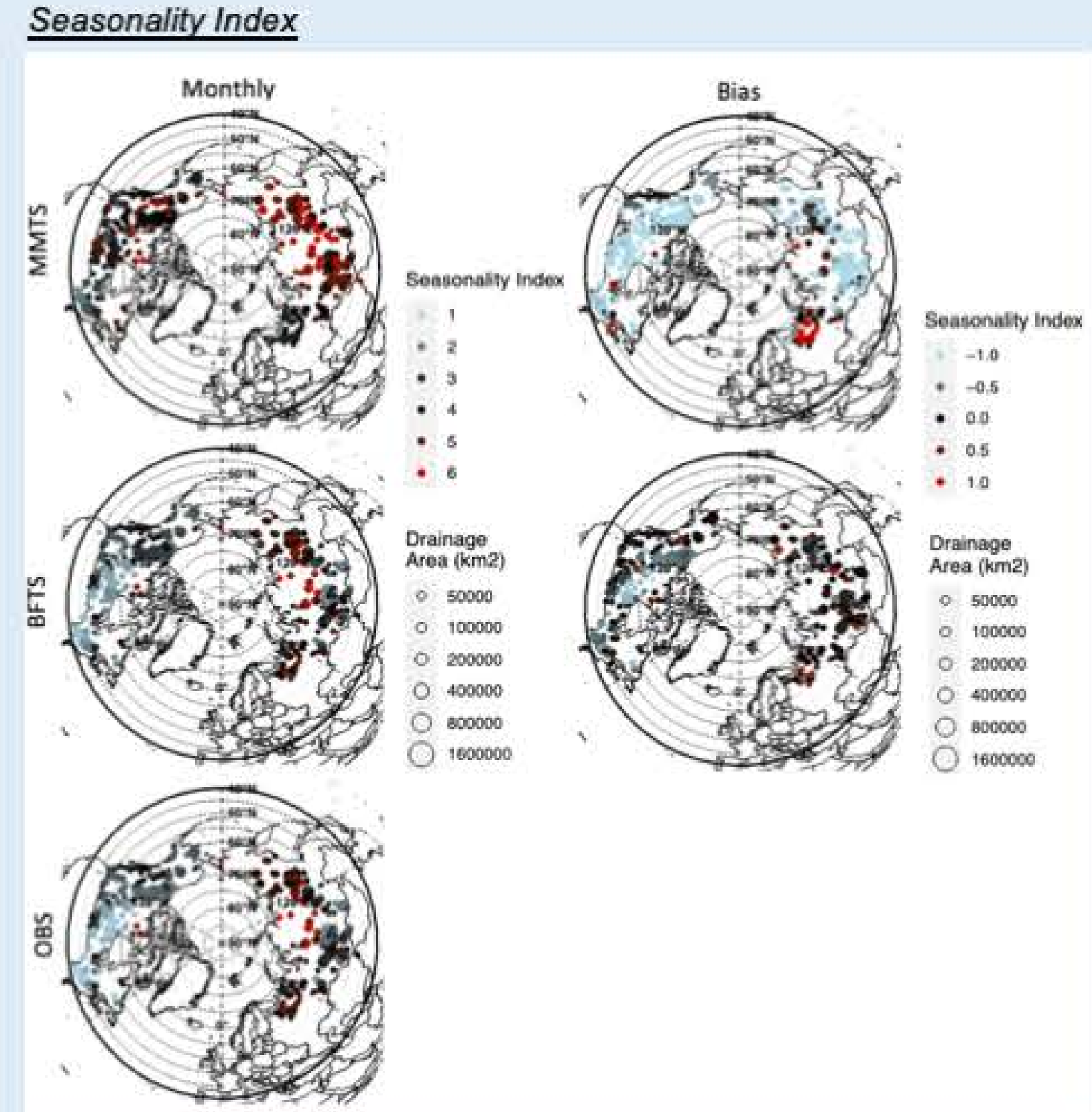
7Q10 Low Flow



Center Timing



Seasonality Index



- Models tend to over-predict Q100 high flow, but under-predict 7Q10 low flow
- Latitudinal gradient present for center timing with CT occurring later in year for more northern latitudes and earlier for southern latitudes
- Little to no seasonality in flows over eastern Canada, stronger seasonality in Russia
- Models tend to underpredict both CT and SI
- Best-fit model approach represents CT & SI well with notable poorer performance (underprediction) persisting over central to eastern Canada

Next Steps: Outcomes from this study can inform which aspects of streamflow change under future climate should be considered, given the fidelity of the models. Future efforts can then involve comparing future changes in streamflow across models, as appropriate.