Hydrol. Earth Syst. Sci. Discuss.

Manuscript Number: doi:10.5194/hess-2016-469, 2016

Title: Evaluating uncertainties in modelling the snow hydrology of the Fraser River Basin, British Columbia, Canada

General comments

The objectives of this study, which focuses on the modelling of snow hydrology of the Fraser River Basin (FRB) of British Columbia (BC), Canada, using the Variable Infiltration Capacity (VIC) model forced with several high-resolution gridded climate datasets (*i.e.*, . ANUSPLIN, NARR, UW, and PCIC), were to comprehensively assess uncertainties related to: (i) driving datasets, (ii) optimization of model parameters, and (iii) model calibration during cool and warm phases of the Pacific Decadal Oscillation (PDO).

This is a very well-written paper that deals with relevant subject matters to the hydrological modelling community. The paper delivers sound results with respect to objective (i), however, I believe those associated with objectives (ii) and (iii) are somewhat incomplete. All the results are discussed with respect to mean values. I believe the strength of the paper would be increased if the interannual variability was discussed as well. Moreover, at the end of the paper, the reader is left with an incomplete take-home message; which begs the following question: how could we use the outcomes of the paper if we were asked to run the model to answer questions related to hydroelectric development or other water resources management issue in the FRB? Something is missing here, like a solid recommendation. Here are a few suggestions I can take from the paper: whenever hydrological modelling is performed one should: (i) analyse the stream flow record with respect to previously identified teleconnection correlations? (ii) perform various calibrations in order to find the optimal set of parameter values? (iii) have several snow elevation bands, may be every 100 m? The readers want a clear take-home message from the authors on how to use their findings. Incidentally, the authors made such a reference in the introduction of the paper, but did follow through in their conclusion (last sentence on p. 4, lines 18-20).

I have made suggestions in the following list of specific comments below on how to fulfill what I perceive as shortcomings. As a side note, I found a bit difficult the exercise of jumping back and forth between the content of the main manuscript and that of the Supplemental File. Perhaps, the introduction of the content of the Supplement File and the content of Section 3.1 could be transformed into a useful technical note.

That being said, I strongly encourage the authors to address these comments as I feel the paper could certainly be a significant contribution to the community.

Specific comments

- To my knowledge several researchers have conducted studies related to objective (i) of this paper and, thus, the authors should consult the following references and relate their work accordingly:
    - Essou, G.R.C., R. Arsenault, R., F.P. Brissette. 2016. Comparison of climate datasets for lumped hydrological modeling over the continental United States. *J. of Hydrology*, **537**: 334-345.
    - Essou, G.R.C., F. Saberly, P. Lucas-Picher, F.P. Brissette, A. Poulin. 2016. Can Precipitation and Temperature from Meteorological Reanalyses Be Used for Hydrological Modeling? *J. of Hydrometeorology*, DOI: 10.1175/JHM-D-15-0138.1
    - Arsenault, R., F.P. Brissette. 2014. Continuous streamflow prediction in ungauged basins: the effects of equifinality and parameter set selection on uncertainty in regionalization approaches. *Water Resour. Res*., **50** (7): 6135–6153
    - Sabarly, F., G. Essou, P. Lucas-Picher, A. Poulin, F. Brissette, 2016: Use of Four Reanalysis Datasets to Assess the Terrestrial Branch of the Water Cycle over Quebec, Canada. *Journal of Hydrometeorology*, **17**, 1447-1466
- To my knowledge, two other studies have dealt with the problem of using calibration and validation series that have different climatological characteristics (objective (iii) of the paper), those of Klemeš (1986. Operational testing of hydrological simulation models. *Hydrolog. Sci. Journal* **31**(1): 13-24) and Seiller *et al*. (2012. Multimodel evaluation of twenty lumped hydrological models under contrasted climate conditions. *Hydrology and Earth System Sciences*, European Geosciences Union, **16** (4): 1171-1189.).
    - In the introductory section of the manuscript, I invite the authors to relate objective (iii) of the study with the content of the aforementioned papers.
- P. 5, line 19: the authors refer to Islam *et al*. (2016), but it is missing from the list of references.
- P. 14, lines 4-6, it is written: « The VIC model calibration is applied to the Fraser River's main stem at Hope, BC and the FRB's major sub-basins, namely the Upper Fraser at Shelley (UF), Stuart (SU), 5 Nautley (NA), Quesnel (QU), Chilko (CH) and Thompson-Nicola (TN) Rivers (Fig. 1a and Supplementary Table 1). »
    - Does this mean there is a set of parameter values different for each sub-basin and one for the drainage area between Hope and the outlet of each sub-basin? It is common practice to do so with many distributed models, but I do not see anywhere in the paper the performance of the model with respect to each sub-basin outlet. Have I missed something?
- P. 14, lines 16-18: to be consistent, should not the five-year spin up period been applied to all gridded datasets; that is from 1979 to 1985; or loop over at least a couple of years until convergence is achieved and then undertake the calibration exercise?
- P. 15, lines 4-11: Why using the PCIC gridded dataset for the optimizer uncertainty runs? Why modifying the parameter space? Why not conducting several optimizer

uncertainty runs and look at the various local optima? That is what is usually done. By reducing the parameter space, the authors are restricting, in theory, the number of local optima, yet there could still be several of them in this modified space. At the end we get three sets of local optima, yet there are multiple other sets. This is an interesting twist, but:

  - Please provide more details on this calibration strategy. The outcome of this work is incomplete as I believe there should have been multiple calibrations for each experiment in order to fully illustrate the equifinality. Please discuss.

- P. 15, lines 12-21: why not six (6) experiments to fully explore the question (2 cool phases x 3 warm phases)?
  - This is an interesting experiment, yet I believe it is incomplete as not all possibilities were explored (see Seiller *et al*., 2012).
  - Are not there any other highly-impacting teleconnection that affect the basin hydrology (*e.g*., ENSO)?
- P. 16, lines 2-3: Perhaps the three regions mentioned here should be depicted on the related Figures, that those figures where knowledge of the region is warranted to follow what is presented and discussed in the paper (Figure 4 in the manuscript and Figures 1-3 and 6 in the Supplement File).
- Given the results introduced in Section 3.1, I think it would have been interesting to have the following calibration parameters: snow-to-rainfall temperature threshold and a vertical temperature gradient.
  - Does the VIC model have such parameters? If that is the case, why not calibrating them?
  - Is there a publication that has introduced a formal sensitivity analysis of the VIC model?
  - Why focusing on soil-related parameters solely and not others as well? In other words, the authors should first introduce to the readers all the model parameters and provide a rationale for their choice.
- P. 19, lines 12-15: « The lower SWE in the NARR-VIC simulation is probably due to the warmer air temperature during winter and spring (Fig. 2b). Winter temperatures being warmer in the NARR dataset may alter the phase of precipitation partitioning with more rainfall than snowfall, and hence less SWE in the NARR-VIC simulation. »
  - This is formulated as a hypothesis, but do not the authors have the input precipitation dataset to validate this hypothesis?
- P.20, line 4: what about a sensitivity analysis of the impact of the number of elevation bands on the output variables of interest? Why ten in other words, why not twenty?
- P.22, Section 3.2.2: for each gridded dataset – VIC simulation what about calculating a runoff to precipitation coefficient to make inferences about model robustness?
- P.24, line 5: « …(Troin *et al*., 2015, 2016)…» Please check as there is only one Troin *et al*. in the list of reference!

- P.26, lines 17-19: « For each set of calibration experiments, the calibration parameters are different, which affects the air temperature lapse rates and thus evapotranspiration, the formation of the snowpack, and the timing of snowmelt. »
    - I thought the temperature lapse rate was not a calibration parameter or is it?
- P.28, lines 5-6: « The trend analysis further highlighted uncertainties of the NARR Dataset. »
    - Uncertainties in terms of what...I am not sure I follow well the authors here. Please provide additional details.
- P29, line 3-4: is not the following sentence « Improving the quality of precipitation data may thus lead to more accurate hydrological responses in the FRB. » contradicting this other sentence « Thus uncertainties in air temperatures are more crucial for hydrological simulations over the FRB rather than those in precipitation» on page , lines 13-14?
    - Please help me here!
- P.29, line 12: not being familiar with the FRB, I was a bit surprise to learn here that the authors had never mentioned in the description of the basin that there are glaciers in the study area!
- P.29, lines 14-15: « Such structural uncertainties need to be evaluated by examining multiple hydrological models over the same region. »
    - That is fine to mention that, but this statement does not have anything to do with what was presented in the paper...why bring this issue and others up at this point, on top of it in the conclusion...maybe there should be a subsection untitled recommendations for future work

Figures

- Figures 2, 3, 6 & 7
    - What about producing a graph illustrating the daily values of the coefficient of variation so the readers can appreciate the interannual variablity for each data set?
- Figure 2
    - Days with January 1st as Julian day 1? In other words, what are the actual Julian days defining the water Year (1 October to 30 September of the following calendar year)? This comment apply to all relevant graphs introduced in the paper and supplement file.
- Figure 5
    - Boxplots would have been useful to highlight the interannual variability.

Other comments

Other specific comments are all related to verb tense can be found in the annotated manuscript. That is, to improve the reading and understanding I suggest using the past tense instead of the present tense. This may be viewed as an old fashion way of reporting scientific work. Now, I am also open to a strong argument to refute my point of view.

Answer to traditional questions

Is the paper free of errors in logic?

Yes

Do the conclusions follow from the evidence?

Yes.

Are alternative explanations explored as appropriate?

Yes.

Are biases, limitations, and assumptions clearly stated, and uncertainty quantified?

Yes.

Is methodology explained in sufficient detail so that the paper's scientific conclusions could be tested by others?

No, see the above list of specific comments.

Is previous work and current understanding cited and represented correctly?

No, see the above list of specific comments.

Is information conveyed clearly enough to be understood by the typical reader?

Yes

Are all figures and tables necessary, appropriate, legible, and annotated (as appropriate)?

Yes

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Hydrology and Earth System Sciences
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Discussions

Evaluating uncertainties in modelling the snow hydrology of the Fraser River Basin, British Columbia, Canada

Siraj Ul Islam and Stephen J. Déry

Environmental Science and Engineering Program,
University of Northern British Columbia,
3333 University Way, Prince George, BC, V2N 4Z9, Canada

Correspondence to: Stephen J. Déry (sdery@unbc.ca)

Abstract. This study evaluates predictive uncertainties in the snow hydrology of the Fraser River Basin (FRB) of British Columbia (BC), Canada, using the Variable Infiltration Capacity (VIC) model forced with several high-resolution gridded climate datasets. These datasets include the Canadian Precipitation Analysis and the thin-plate smoothing splines (ANUSPLIN), the North American Regional Reanalysis (NARR), University of Washington (UW) and Pacific Climate Impacts Consortium (PCIC) gridded products. Uncertainties are evaluated at different stages of the VIC implementation starting with the driving datasets, optimization of model parameters, and model calibration during cool and warm phases of the Pacific Decadal Oscillation (PDO).

The inter-comparison of the forcing datasets (precipitation and air temperature) and their VIC simulations (snow water equivalent (SWE) and runoff) reveal widespread differences over the FRB especially in mountainous regions. The ANUSPLIN precipitation shows a considerable dry bias in the Rocky Mountains whereas the NARR winter air temperature is 2°C warmer than the other datasets over most of the FRB. In the VIC simulations, the elevation-dependent changes in the maximum SWE (maxSWE) are more prominent at higher elevations of the Rocky Mountains where PCIC-VIC simulation accumulates too much SWE and ANUSPLIN-VIC yields an underestimation. Additionally, at each elevation range, the day of maxSWE varies 10 to 20 days between the VIC simulations. The snow melting season begins early in NARR-VIC simulation whereas PCIC-VIC simulation delays the melting indicating seasonal uncertainty in SWE simulations. When compared with the observed runoff for the Fraser River main stem at Hope, BC, the ANUSPLIN-VIC simulation shows considerable underestimation of runoff throughout the water year owing to reduced precipitation in the ANUSPLIN forcing dataset. The NARR-VIC simulation yields more winter and spring runoff and earlier decline of flows in summer due to a nearly 15-day earlier onset of the FRB springtime snowmelt.

Analysis of the parametric uncertainty in the VIC calibration process shows that the choice of the initial parameter range plays a crucial role in defining the model hydrological response for the FRB. Furthermore, the VIC calibration process is biased toward cool and warm phases of the PDO and the choice of proper calibration and validation time periods is important for the experimental setup. Overall the VIC hydrological response is prominently influenced by the uncertainties involved in the forcing datasets rather than those in its parameters optimization and experimental setups.

Keywords: Uncertainties, hydrological modelling, climate datasets, runoff, calibration, Fraser River

1 Introduction

While advances in computational power and ongoing developments in hydrological modelling have increased the reliability of hydrologic simulations, the issue of adequately addressing the associated uncertainty remains challenging (Liu and Gupta, 2007). There is a growing need for proper estimation of uncertainties associated with hydrological models and the observations required to drive and evaluate their outputs. Hydrological simulations of snow processes and related hydrology depend critically on the input climate forcing datasets, particularly the precipitation and air temperature (Reed et al., 2004; Mote et al., 2005; Tobin et al., 2011). Both of these input forcings regulate the quantity and phase of modelled precipitation and affect the response of simulated snow accumulation and runoff. The model results therefore rely heavily on the quality of these forcings as the uncertainty (measurement errors, etc.) in such data will propagate through all hydrological processes during simulations (Wagener and Gupta, 2005; Anderson et al., 2007; Tapiador et al., 2012). The uncertainties in hydrological simulations also arise from the model parameters, its structure and in the measurement of the response metric that is used for model calibration. Hence the reliability of input forcings along with the capability of the hydrological model and the experimental setup ultimately determine the fate of hydrological variables essential for water resource management.

Several observed gridded climate datasets of precipitation and air temperature (Mesinger et al., 2006; Hopkinson et al., 2011), based on available observational data, post-processing techniques and, in some cases, climate modelling, are currently available over the Canadian landmass to facilitate climate and hydrological simulations. These datasets provide long term gridded precipitation and air temperature records on hourly and daily bases making them especially useful for hydrological simulations, particularly over areas where in situ station densities are low. However, these datasets, being spatially interpolated or assimilated to gridcells, rely mainly on the spatial density of the observational network, which is often quite low in mountainous regions (Rinke et al., 2004). Observational data incorporated into gridded datasets may also contain measurement errors and missing records that translate into the data interpolation and contribute to the overall uncertainty in gridded data products. Such uncertainties are assessed in many studies focusing on the forcing data (Horton et al., 2006; Graham et al., 2007; Kay et al., 2009; Eum et al., 2014).

The quality of hydrological modelling depends on how well a model simulates the regional detail and topographic characteristics of the region, especially in mountainous regions. However, most mountainous regions exhibit higher errors in gridded datasets because they are usually based on an uneven number of stations that are mostly located at lower elevations (Eum et al., 2012). This is true for most large basins in western Canada that exhibit highly variable elevation ranges and strong climatological heterogeneity. One such large basin is British Columbia's (BC's) Fraser River Basin (FRB), which is vital for Canada's environment, economy and cultural identity. Its mountainous snowpack serves as a natural reservoir for cold-season precipitation, providing snowmelt driven flows in summer. Evaluating uncertainties in modelling the FRB's hydrology is crucial for informed decision-making and water resources management. This includes the communication of the uncertainties, propagated into the model predictions, in an appropriate manner to decision makers or stakeholders, thereby allowing confidence in the model results.

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Although the currently available gridded datasets (reanalysis and interpolated) over the FRB are derived from observational stations using various interpolation and assimilation techniques, they may still have systematic biases because of their grid resolution, the density of the surface station network used for data assimilation and the topographic characteristics of the FRB. In the FRB, 23% of the basin exceeds 1500 m in elevation whereas roughly 5% of the in situ meteorological stations surpasses this elevation (Shrestha et al., 2012). Such mismatch between station densities at different elevations makes the precipitation interpolation at higher elevations excessively influenced from the lower elevation stations (Stahl et al., 2006; Rodenhuis et al., 2009; Neilsen et al., 2010). Therefore, despite extensive implementation of hydrologic modelling with single observed forcings (Shrestha et al., 2012; Kang et al., 2014, 2016, etc.), evaluation of the uncertainties in forcing datasets remains a critical and challenging issue for the FRB. As such, the first step is to evaluate available observation-based forcing datasets for their suitability to be used in hydrological modelling over the FRB.

In Canada, numerous studies have assessed the performance of the hydrologic simulations driven by only one particular driving dataset (Pietroniro et al., 2006; Choi et al., 2009; Bennett et al., 2012; Kang et al., 2014). Eum et al. (2014) recently compared hydrological simulations driven by several high-resolution gridded climate datasets over western Canada's Athabasca watershed and found significant differences across the simulations. While BC's snowpacks and hydrology are well studied in the literature (Danard and Murty, 1994; Fleming et al., 2006; Choi et al., 2010; Thorne and Woo, 2011; Déry et al., 2012; Shrestha et al., 2012; Kang et al., 2014, 2016; Islam et al., 2016; Trubilowicz et al., 2016), detailed inter-comparisons of available observational forcing in terms of their hydrological response is not thoroughly analysed, particularly over the FRB's complex topography. In this study, we

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therefore investigate the simulated hydrological response of uncertainties associated with air temperature and precipitation forcing on the FRB's mountainous snowpack and runoff. To achieve this, four forcing datasets, namely the Canadian Precipitation Analysis and the thin-plate smoothing splines (ANUSPLIN hereafter; Hopkinson et al., 2011), the North American Regional Reanalysis (NARR hereafter; Mesinger et al., 2006), University of Washington (UW hereafter; Shi et al., 2013) and Pacific Climate Impacts Consortium (PCIC hereafter; Shrestha et al., 2012) gridded products are applied to the FRB. These datasets are explored across three different regions and multiple elevation ranges. Over the FRB region, while the PCIC and UW datasets are individually used in Shrestha et al. (2012) and Kang et al. (2014, 2016) to drive the VIC hydrological model, the NARR and ANUSPLIN datasets are not yet evaluated. However, the NARR dataset is used in studies focusing on other regions of Canada (Woo and Thorne, 2006; Choi et al, 2009; Ainslie and Jackson, 2010; Eum et al., 2014; Trubilowicz et al., 2016). To our knowledge, this is the first comprehensive study that examines these datasets collectively based on the spatial and elevation dependent hydrological response.

Along with forcing datasets, many studies have focused their attention either on model structure (Wilby and Harris, 2006; Jiang et al., 2007; Ludwig et al., 2009; Poulin et al., 2011; Velazquez et al., 2013) or on calibration parameters (Teutschbein et al., 2011; Bennett et al., 2012). For parameter uncertainty, a hydrological model can have many equivalent local optima within a realistic parameter space (Poulin et al., 2011). Therefore, several different parameter sets may be available for the same ''optimal'' measure of efficiency during the optimization process (i.e. parameter non-uniqueness; Beven, 2006). Here we evaluate the parameter uncertainties involved in the model calibration process, i.e. calibration optimizer sensitivity to parameter initial limits. Moreover we focus on another unique aspect of modelling uncertainty related to the selection of time periods for model calibration and validation under changing climatic conditions on decadal time scales. In this case, the model uncertainty is estimated by first analysing the FRB's air temperature and precipitation teleconnections with cool and warm phases of the Pacific Decadal Oscillation (PDO).

Overall, the main goals of this study are: (i) to compare and identify the most reliable available gridded forcing datasets for the hydrological simulations over the FRB region; (ii) to evaluate hydrological modelling responses of different driving datasets over a range of FRB elevations; (iii) to assess the uncertainty involved in the model calibration process by focusing on parameter optimization; and (iv) to evaluate the calibration process under changing climatic conditions.

To analyse the FRB's snowmelt-driven hydrology, the macroscale Variable Infiltration Capacity (VIC) hydrological model (Liang et al., 1994, 1996) is used as the simulation tool. The VIC model conserves surface water and energy balances for large-scale watersheds such as the FRB (Cherkauer et al., 2003). It has been successfully implemented, calibrated and evaluated over the FRB (Shrestha et al., 2012; Kang et al., 2014; Islam et al., 2016).

The remainder of this paper is structured as follows. Section 2 discusses the FRB, the VIC model, the driving datasets and experimental setup. Section 3 describes the forcings inter-comparison, hydrological simulations, parameter sensitivity and uncertainly related to the PDO. Section 4 summarizes and concludes this study.

2. Study Area, Model and Methodology

2.1 Fraser River Basin (FRB)

The FRB is one of the largest basins of western North America spanning 240,000 km^2 of diverse landscapes with elevations varying from sea level to Mount Robson, its tallest peak at 3954 m above sea level (Benke and Cushing, 2005). It covers the mountainous terrain of the Coast and Rocky Mountains along with dry central plateaus (Fig. 1). The FRB's headwaters are in the Rocky Mountains with its major tributaries the Stuart, Nechako, Quesnel, Chilcotin, Thompson, and Harrison Rivers. The Fraser River runs 1400 km through the Fraser Canyon before reaching Hope, BC, where it veers westward to drain into the Salish Sea and the Strait of Georgia at Vancouver, BC (Benke and Cushing, 2005; Schnorbus et al., 2010).

In winter, considerable amounts of snow normally accumulate at higher elevations, except in coastal areas. In late spring and early summer, snowmelt from higher elevations induce peak flows in the main stem of the Fraser River and its many tributaries (Moore and Wondzell, 2005), which rapidly decline in late summer following the depletion of snowmelt. Owing to its complex mountainous ranges, the FRB's hydrologic response varies considerably across the basin, differentiating it into snow-dominant, hybrid (rain and snow), or rain-dominant regimes (Wade et al., 2001).

2.2 Variable Infiltration Capacity (VIC) Model

The VIC model resolves energy and water balances and therefore requires a large number of parameters, including soil, vegetation, elevation, and daily meteorological forcings, at each gridcell. To evaluate hydrological responses over complex terrain, the model simulates the subgrid variability in topography and precipitation by dividing each gridcell into a number of snow elevation bands (Nijssen et al., 2001b). The model utilizes a mosaic-type representation by partitioning elevation bands into a number of topographic tiles that are based on high-resolution spatial elevations and fractional area. The snow model embedded in the VIC model is then applied to each elevation tile separately (Gao et al., 2009).

The VIC model is widely used in many hydrological applications including water availability estimation and climate change impacts assessment in North America (Maurer et al., 2002; Christensen and Lettenmaier, 2007; Adam et al., 2009; Cuo et al., 2009; Elsner et al., 2010; Gao et al., 2010; Wen et al., 2011; Oubeidillah et al., 2014;) and around the world (Nijssen et al., 2001a,b; Haddeland et al., 2007; Zhou et al., 2016). It is also commonly used to simulate hydrologic responses in snowmelt-dominated basins (Christensen and Lettenmaier, 2007; Hidalgo et al., 2009; Cherkauer and Sinha, 2010; Schnorbus et al., 2011).

2.3 Datasets

Along with recent developments in hydrological models, several observation-based gridded datasets are now available to drive the models such as ANUSPLIN, NARR, UW and PCIC. These meteorological forcing datasets are developed using high-resolution, state-of-the-art data interpolation and (for NARR only) assimilation techniques. This is to improve the quality of forcing data to analyse a model’s hydrological response over of any particular basin.

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The ANUSPLIN dataset, developed by Natural Resources Canada (NRCan), contains gridded data of daily maximum and minimum air temperature (°C), and total daily precipitation (mm) for the Canadian landmass south of 60°N at ~10 km resolution (NRCan, 2014). This Canadian dataset uses a trivariate thin-plate smoothing spline technique referred to as ANUSPLIN (Hutchinson et al., 2009) with recent modifications (Hopkinson et al., 2011). Eum et al. (2014) used the ANUSPLIN dataset for hydrological modelling over Alberta's Athabasca watershed and reported underestimations in simulated runoff, owing to a dry bias in ANUSPLIN precipitation.

NARR was developed at 32 km spatial and 3-hourly temporal resolution to improve the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) global reanalysis data by employing the Eta Data Assimilation system for the North American domain for the period from 1979 to the current year. The interannual variability of the NARR seasonal precipitation and accuracy of its temperature and winds are found superior to earlier versions of the NCEP/NCAR reanalysis datasets (Mesinger et al., 2006; Nigam and Ruiz-Barradas, 2006). Choi et al. (2009) investigated the applicability of temperature and precipitation data from NARR for hydrological modelling of selected watersheds in northern Manitoba. They found that NARR air temperature and precipitation data are in much better agreement with observations than NCEP–NCAR Global Reanalysis-1 (Kalnay et al., 1996; Kistler et al., 2001) dataset. Woo and Thorne (2006) used precipitation and air temperature data from two global reanalysis datasets and from NARR as input to a hydrological model for the Liard River Basin in western subarctic Canada and reported significant improvement in its hydrological simulations. NARR output has also been used in regional water budget calculations (Luo et al., 2007; Ruane, 2010; Sheffield et al., 2012). Choi et al. (2009) and Keshta and

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Elshorbagy (2011) reported that NARR output are suitable for hydrologic purposes, especially when other observations are unavailable. However, they focused on the Canadian Prairies, where the topography is not complex.

The UW dataset of daily precipitation, maximum and minimum air temperature, and average wind speed are based on the extended gridded UW dataset (Shi et al., 2013; Adam et al., 2006; Adam and Lettenmaier, 2008). Monthly precipitation originates from the University of Delaware observed land surface precipitation product (Matsuura and Willmott 2009), which was adjusted to account for gauge undercatch and was converted to daily data using the high temporal precipitation dataset from Sheffield et al. (2006). Daily wind speeds are extracted from NCEP/NCAR reanalysis datasets (Kalnay et al., 1996).

The PCIC dataset of precipitation, maximum and minimum temperature, and wind speed was derived primarily from Environment and Climate Change Canada (ECCC) climate station observations, with additional inputs from the United States Co-operative Station Network, the BC Ministry of Forests, Lands and Natural Resource Operations, the BC Ministry of Environment's Automated Snow Pillow network, and BC Hydro's climate network (Schnorbus et al., 2011; Shrestha et al., 2012). These data are available at ~6 km resolution and were corrected for point precipitation biases and elevation effects (Schnorbus et al., 2011).

The ANUSPLIN, NARR, UW and PCIC datasets are available at 10 km, 32 km, 25 km and 6 km spatial resolution, respectively, and at a daily time scale. To facilitate comparison, the ANUSPLIN, NARR and PCIC datasets are regridded to 25 km resolution using bilinear interpolation to match the

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scale of the current VIC implementation. To calibrate and validate the VIC model simulated flow, we use daily streamflow data from ECCC's Hydrometric Dataset (HYDAT; Water Survey of Canada 2014). These data are extracted and compiled into a comprehensive streamflow dataset for the FRB spanning 1911–2010 (Déry et al., 2012).

In addition, we compare the simulated SWE with observations from the BC River Forecast Centre's network of snow pillow sites (BC Ministry of Forests, Lands and Natural Resource Operations, 2014). The snow pillow stations record the weight of the accumulated snowpack (SWE) on a daily basis. Based on the availability of data, we use SWE observations from four sites located at Yellowhead (ID: 1A01P) and McBride (ID: 1A02P) in the upper Fraser and at Mission Ridge (ID: 1C18P) and Boss Mountain Mine (ID: 1C20P) in the middle Fraser. Due to the availability of data, we use the 1996-2006 time period for the Yellowhead, Mission Ridge and Boss Mountain Mine snow pillows and 1980-1986 for the McBride location. Detailed information about these sites is available in Kang et al. (2014) and Déry et al. (2014).

2.4 The VIC Implementation

The VIC model, as set up by Kang et al. (2014) and Islam et al. (2016) for the FRB, is employed for evaluating the model's ability to simulate the FRB's hydrological response when driven by different observational forcings. The model was previously applied to the FRB to investigate its observed and projected changes in snowpacks and runoff. In this study, we perform model integrations over the entire FRB using gridcells composed of 34 rows and 42 columns spanning 48°– 55°N and 119°–131°W. The model is configured at 0.25° spatial resolution using a daily time step, three soil layer depths and ten

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vertical snow elevation bands. Once an individual VIC simulation is completed, the runoff for the basin is extracted at an outlet point of the given sub-basin, using an external routing model that simulated a channel network (adapted from Wu et al. (2011)) with several nodes (Lohmann et al., 1996; 1998a, b). Streamflow is converted to areal runoff by dividing it by the corresponding sub-basin area. Daily runoff at the outlet cell is integrated over time to obtain total annual runoff for a selected basin. Other than the calibration parameters, the soil and vegetation parameters, leaf area index (LAI) and albedo data are kept identical as per the VIC model implementation to the FRB reported in Kang et al. (2014).

2.4.1 Calibration

To explore the feasible parameter space, we use the University of Arizona multi-objective complex evolution (MOCOM-UA) optimizer for the VIC calibration process (Yapo et al., 1998; Shi et al., 2008). MOCOM-UA searches a set of VIC input parameters using the population method to maximize the Nash–Sutcliffe efficiency (NSE) coefficient (Nash and Sutcliffe, 1970) between observed and simulated runoff. Six soil parameters are used in the optimization process, i.e. b_infilt (a parameter of the variable infiltration curve), Dsmax (the maximum velocity of base flow for each gridcell), Ws (the fraction of maximum soil moisture where nonlinear base flow occurs), D2 and D3 (the depths of the second and third soil layers), and Ds (the fraction of the Dsmax parameter at which nonlinear base flow occurs). Final values of these six calibrated parameters are estimated for each forcing dataset by a number of simulation iterations minimizing the difference between the simulated and observed monthly flow.

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While the MOCOM-UA automated optimization process utilizes monthly streamflow in calibration, we evaluated the overall model performance on daily time scales using NSE and correlation performance metrics.

The VIC model calibration is applied to the Fraser River's main stem at Hope, BC and the FRB's major sub-basins, namely the Upper Fraser at Shelley (UF), Stuart (SU), Nautley (NA), Quesnel (QU), Chilko (CH) and Thompson-Nicola (TN) Rivers (Fig. 1a and Supplementary Table 1). These sub-basins contribute 75% of the annual observed Fraser River discharge at Hope, BC with the largest contributions from the TN, UF and QU sub-basins (Déry et al., 2012).

2.4.2 Experiments

A series of different VIC experiments are performed to i) compare the VIC model's response when driven by different forcings, ii) evaluate the uncertainties related to the VIC optimizer, and iii) investigate the effect of PDO teleconnections on the VIC calibration and validation time periods. These experiments are categorized as below:

1) **Inter-comparison runs:** The VIC model is driven by each forcing dataset for 28 years (1979 to 2006) with 1979-1990 as the calibration period and 1991-2006 as the validation period using the MOCOM-UA optimizer. The VIC simulations driven by ANUSPLIN, UW and PCIC forcings are initiated five years prior to the year 1979 to allow model spin-up time. Since NARR is not available until 1979, the model spin up time is not considered. Once calibration is completed, validation runs are initiated with five different initial conditions (lagged by 24-hour intervals) to avoid any random uncertainties such as those in initial conditions (Table 1). The ANUSPLIN, NARR, UW and PCIC

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driven ensemble mean VIC simulations are named as ANUSPLIN-VIC, NARR-VIC, UW-VIC and PCIC-VIC, respectively. These ensemble simulations are run for the whole FRB and its UF, SU, NA, QU, CH and TN sub-basins.

2) **Optimizer uncertainty runs:** Here the VIC model is driven only by the PCIC dataset for the 1979-1990 calibration time period using the MOCOM-UA optimizer. We perform the optimization of six soil parameters, i.e. b_infilt, Dsmax, Ws, D2, D3 and Ds in three experimental setups using different initial ranges of parameter limits. The VIC calibration experiments (OPT1 and OPT3) are run using two narrow ranges selected from the maximum limits of calibration parameters. The same experiment is then run with maximum limits of the calibration parameters (OPT2). Calibration parameters, their initial ranges and final optimized values for all three experiments are given in Table 3. The OPT1, OPT2 and OPT3 simulations are run over the whole FRB only.

3) **PDO uncertainty runs:** Both the UW and PCIC datasets are used to drive long term (1950-2006) VIC simulations. This is to capture the decadal variability of cool and warm phases of the PDO. Along with this, three different experiments, namely PDO1, PDO2 and PDO3 are performed with calibration periods of 1981-1990, 1956-1965 and 1967-1976 and with corresponding validation periods of 1991-2001, 1966-1976 and 1977-1987, respectively (Table 4). Each time period is selected to capture cool or warm PDO phases, i.e. its cool (1956-1965 and 1967-1976) and warm (1981-1990, 1991-2001 and 1977-1987) phases. For each calibration experiment in one particular phase of the PDO, the MOCOM-UA is used to optimize calibration parameters. The NSE is calculated for the calibration and validation periods using the daily observed streamflow data for the Fraser River at Hope. All PDO simulations are run over the whole FRB only.

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2.5 Analysis Strategy

The analyses are performed for three FRB hydro-climatic regimes: the Interior Plateau, the Rocky Mountains and the Coast Mountains (Moore, 1991). These three regions are chosen given their distinct physiography and hydro-climatic conditions. The gridcell partitioning of these three regions and their elevations are shown in Fig. 1b. Results in this study mainly focus on the Fraser River main stem at Hope, BC since it covers 94% of the basin's drainage area and has a continuous streamflow record over the study periods. However, the inter-comparison runs are also compared over FRB's major sub-basins. The total runoff is calculated using the sum of baseflow and runoff. Seasonal variations are assessed by averaging Dec-Jan-Feb (DJF), Mar-Apr-May (MAM), Jun-Jul-Aug (JJA) and Sep-Oct-Nov (SON) months for winter, spring, summer and autumn, respectively.

In the SWE analysis, the snowmelt is calculated by taking the difference between maximum and minimum SWE over the water year (1 October to 30 September of the following calendar year). The corresponding day of the water year having maximum SWE (maxSWE) is named as maxSWE-day.

The Mann–Kendall test (Mann, 1945; Kendall, 1970) is used to estimate monotonic trends in the input forcing data and the simulated hydrological variables. This non-parametric trend test has been used in several other studies to detect changing hydrological regimes (Lettenmaier et al., 1994; Ziegler et al., 2003; Déry et al., 2005; Kang et al., 2014). Trends are considered to be statistically-significant when $p < 0.05$ with a two-tailed test.

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3 Results and Discussion

We first examine the ANUSPLIN, NARR, UW and PCIC datasets to investigate how substantial are the differences in precipitation and temperature at several temporal and spatial scales across the FRB and its sub-regions. The VIC simulations, driven by these forcing datasets, are then discussed to evaluate uncertainties in simulated SWE and runoff. This is followed by the discussion of uncertainty in the VIC calibration process.

3.1 Forcings Datasets Inter-comparison

The daily mean air temperature of ANUSPLIN, NARR, UW and PCIC datasets remains below 0°C from November to March and rises above 0°C in early spring over all three FRB sub-regions (Fig. 2). While the inter-datasets seasonal variability of air temperature is quite similar, the winter in NARR is ~2°C warmer compared to the remaining datasets. The grid scale seasonal differences (PCIC minus ANUSPLIN, NARR and UW) of mean air temperature (Supplementary Fig. 1) spatially quantify the inter-datasets disagreements. While the PCIC-ANUSPLIN and PCIC-UW differences are within ±1°C, the PCIC-NARR difference exceeds 2°C over most of the FRB in DJF and SON, revealing NARR air temperatures to be quite warmer than in the PCIC dataset.

The magnitudes of daily mean precipitation vary markedly amongst datasets. Winter precipitation, which begins in November and persists until April, shows greater inter-datasets differences, particularly over the Rocky and Coast Mountains. Compared to the PCIC and UW datasets, the ANUSPLIN precipitation is underestimated in all three regions with nearly 2.0 mm day^{-1} to 5.0 mm day^{-1} differences in the Rocky and Coast Mountains, respectively. This underestimation is more evident in the

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PCIC-ANUSPLIN spatial difference (Supplementary Fig. 2) revealing up to 5 mm day^{-1} difference over the mountainous regions. The precipitation differences in the Interior Plateau remain nearly zero for all the datasets. The maximum intraseasonal variability arises in the Coast Mountains ranging from 10.0 mm day^{-1} in winter and nearly zero in summer. The range of inter-datasets spread for peak precipitation varies from 5.0 mm day^{-1} to 10.0 mm day^{-1} during winter for the Coast Mountains. Precipitation in the Coast Mountains is more variable due to its proximity to the Pacific Ocean where the interaction between steep elevations and storm track positions is quite complex. In the Coast Mountains, the NARR precipitation is underestimated and is comparable to ANUSPLIN.

The underestimation of the ANUSPLIN mountainous precipitation is probably due the thin plate smoothing spline surface fitting method used in its preparation. For NARR, air temperature and precipitation uncertainties may have been induced by the climate model used to assimilate and produce the reanalysis product.

3.2 Hydrological Simulations

The ANUSPLIN-VIC, NARR-VIC, UW-VIC and PCIC-VIC simulation performance is [1] evaluated using the NSE and correlation coefficients by calibrating and validating against observed daily streamflow for the Fraser River at Hope (Table 2). The NSE scores are much higher for the PCIC-VIC and UW-VIC simulations compared to the ANUSPLIN-VIC and NARR-VIC. The lower NSE score in the ANUSPLIN-VIC simulation reflects dry precipitation bias in the ANUSPLIN dataset. As the model configuration, resolution, and soil data are [2] identical for all VIC simulations, different NSE values reveal uncertainty associated only with each observational forcing dataset. Despite the low NSE score of the

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ANUSPLIN-VIC simulation, the correlation coefficient is significantly high. The bias in the simulated streamflow is contributing to the lower NSE coefficient whereas the phase of seasonal flow is quite similar to the observed flow in the ANUSPLIN-VIC simulation. There may be additional sources of uncertainty due to the method used to assess simulation accuracy. For example, instead of using NSE, other model evaluation metrics such as the Kling-Gupta Efficiency (KGE) coefficient (Gupta et al., 2009) may produce different levels of model accuracy.

The ANUSPLIN-VIC, NARR-VIC, UW-VIC and PCIC-VIC simulated SWE and snowmelt, areally-averaged over the FRB's three sub-regions, show similar seasonal variability but considerably different magnitudes, especially over mountainous regions. Figure 3a shows these differences for the Rocky Mountains revealing the range of peak SWE from 400 mm for ANUSPLIN to >600 mm for PCIC. The dry bias in ANUSPLIN precipitation forcing induces lower SWE magnitude in the ANUSPLIN-VIC simulation. The lower SWE in the NARR-VIC simulation is probably due to the warmer air temperature during winter and spring (Fig. 2b). Winter temperatures being warmer in the NARR dataset may alter the phase of precipitation partitioning with more rainfall than snowfall, and hence less SWE in the NARR-VIC simulation. Such differences in SWE are reflected in the associated snowmelt (Fig. 3b) where the NARR-VIC simulation shows earlier snowmelt. This is further investigated by VIC sensitivity experiments and is discussed later in the text. Grid-scale differences in simulated SWE (Fig. 4) and runoff (Supplementary Fig. 3) arise most notably over the mountainous regions. In the interior FRB, the simulation differences between PCIC-VIC and ANUSPLIN-VIC means SWE are within 10 mm range whereas such differences exceed 50 mm to 100 mm range for the NARR-VIC and UW-VIC simulations.

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In the FRB's mountainous regions, the VIC model can lead to inaccurate snowpack estimates if the elevation dependence on snow accumulation and ablation are not modelled properly. As mentioned in section 2.4, we use ten elevation bands in our VIC implementation so that each band's mean elevation is used to lapse the gridcell average air temperature and precipitation to produce more reliable estimates. We cluster the elevation distribution within 10 bands into different elevation ranges. This allows in-depth analysis of the elevation dependent variation of mean SWE that is of particular importance for the Rocky and Coast Mountains regions of the FRB. We examine the magnitude of maxSWE and corresponding maxSWE-day of the water year between all simulations and elevation ranges (Fig. 5). The difference in maxSWE between all VIC simulations increases with elevations, particularly the Rocky Mountains where higher elevations (>1400 m) show large disagreement between simulated maxSWE (Fig. 5a). In the Interior Plateau, the NARR-VIC simulated maxSWE exceeds 300 mm whereas all other simulations are within 200 mm. The maxSWE elevation dependent variation is quite complex in the Coast Mountains. However the simulations differences at elevations >1400 m are smaller compared to the lower elevations below 1000 m. Apart from maxSWE magnitude, the maxSWE-day variation differs considerably across the VIC simulations. Generally, the maxSWE-day varies by ~2 months between lower and higher elevations as snow onset occurs later in autumn. While the maxSWE-day variation is quite complex within each elevation range, the NARR-VIC maxSWE-day is earliest whereas PCIC-VIC delays the snow accumulation over the 600-2000 m elevation range in the Rocky Mountains. There is nearly 20 days of simulations variation at the Rocky Mountains highest elevation range. Such variation highlights the uncertainties in seasonality of the VIC simulated

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snowpacks. For the Interior Plateau and the Coast Mountains, no consistent pattern of maxSWE-day variation exists for any particular simulation.

3.2.1 Simulated SWE comparison with observations

As mentioned earlier, all gridded climate forcing datasets are based on station observations. The density of stations in the FRB's mountainous regions remains quite low and therefore induces higher uncertainties in the observational gridded products. It is important to quantify the spatial discrepancy between the simulated (0.25° gridcell) and observed (snow pillow station dataset) SWE that may lead to an uncertainty in snow estimations by models (Elder et al., 1991; Tong et al., 2010). We use observed SWE from BC snow pillow sites and the VIC simulated SWE data over the same elevation and overlapping continuous time periods at four different locations in the upper and middle Fraser where a high volume of SWE accumulates seasonally.

The daily time series of VIC simulated SWE (Supplementary Fig. 4) follows the observed interannual variability in snow accumulation but with considerable differences across simulations. The PCIC-VIC simulation accumulates too much SWE compared to observations in the gridcell corresponding to the Yellowhead location. This overestimation is further explored for Yellowhead by expanding the time series back to 1979 (not shown), which reveals issues with PCIC precipitation data only during 1996-2004 exhibiting considerable above normal anomalies at Yellowhead. While ANUSPLIN-VIC shows lower SWE amounts, the NARR-VIC and UW-VIC simulations reproduce the observed variation quite reasonably for Yellowhead. For McBride, all simulations are more or less comparable except ANUSPLIN-VIC showing a SWE underestimation compared to observations. In the middle Fraser, the

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UW-VIC simulation is quite comparable to observations whereas the PCIC-VIC simulation underestimates SWE at Mission Ridge. Both ANUSPLIN-VIC and NARR-VIC underestimate SWE in the middle Fraser locations. The observed SWE values in the lower Fraser locations are not well captured by VIC, perhaps owing to the region's coastal influence and strong sensitivity to air temperatures (not shown). These results highlight the importance of accurate precipitation forcings to simulate SWE. Along with this, even small perturbations in air temperature can change the phase of precipitation, which directly contributes to changes in SWE accumulation.

3.2.2 Simulated Runoff comparison with observations

The VIC simulated flows are routed to produce hydrographs for the Fraser River at Hope, BC (Fig. 6). Comparison of simulated runoff with observations shows the highly consistent model performance for PCIC-VIC and UW-VIC simulations whereas the runoff is considerably lower for the ANUSPLIN-VIC simulation. The NARR-VIC hydrograph is comparable in magnitude with observations but the runoff timing is considerably shifted (~15 days) yielding more winter and spring runoff and earlier decline of flows in summer. The shift in the hydrograph is probably caused by the 2°C warmer air temperatures causing earlier snowmelt. This finding is confirmed by a VIC sensitivity experiment where the air temperature is perturbed by 2°C while keeping the precipitation unchanged. Similar to the case of NARR-VIC results, the simulated SWE, snowmelt and runoff decreases with 2°C rises in air temperature forcings. We further produce the hydrographs for the FRB's six major sub-basins to compare VIC simulation runs of each basin. Similar to the hydrograph of the Fraser River at Hope, the ANUSPLIN-VIC runoff shows considerable disagreement with the observed hydrograph, especially in the UF, QU and TN basin owing to the dry bias in its precipitation forcing. Moreover, NARR-VIC

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runoff is overestimated in SU, NA and CH sub-basins whereas for UF, QU and TN, the simulated runoff underestimates observed flows. Consistent with spatial differences of mean air temperature and runoff (Supplementary Figs. 1 and 3), the warmer NARR air temperatures (compared to PCIC) over the SU, NA and CH sub-basins in winter and spring induce more snowmelt and hence overestimate runoff. In contrast, over the UF, QU and TN, the NARR air temperature is comparatively cooler in winter. This may reduce the snowmelt driven runoff causing underestimation over these sub-basins.

Differences seen in the FRB's flow magnitude and timing clarify the impact of forcing uncertainties on the simulations. Such variation in simulated runoff especially during the snow-melting period (Apr-Jul) is either due to the uncertain amount of precipitation or the magnitude of air temperature in the forcing datasets.

We further investigate differences in forcings and their VIC simulation based on their climatic trends. The monthly climate trends in air temperature, precipitation and simulated runoff (Supplementary Fig. 5) shows that the air temperatures warming during winter (up to 3°C in December) with the decline of precipitation (mainly snowfall) is relatively similar between different forcing datasets. The magnitude of trends in the NARR dataset is somewhat lower for air temperature and higher for precipitation compared to the other three datasets. In the simulated runoff, the monthly variation of trends generally agrees among simulations, but the trends are weak in the ANUSPLIN-VIC and UW-VIC simulations whereas the PCIC-VIC and NARR-VIC simulations exhibit strong trends. In the NARR-VIC simulations, runoff trends are affected by lower air temperature and higher precipitation trends yielding increasing runoff. Grid-scale trends show widespread differences in NARR-VIC runoff, particularly in the interior of the FRB when compared to ANUSPLIN-VIC, UW-VIC and PCIC-VIC monthly trends

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(Supplementary Fig. 6). All the four simulations exhibit strong positive runoff trends in April followed by declining trends in May in the Rocky Mountains (the UF and TN sub-basins).

The inter-comparison analysis shows that the uncertainties in forcing datasets contribute substantially to the performance of the VIC model. This is consistent with studies reporting that the uncertainties in model structure contribute less to snowpack and runoff simulations (Troin et al., 2015, 2016) whereas the uncertainties in forcing datasets are the predominant sources of uncertainties (Kay et al., 2009; Chen et al., 2011). Using the NARR dataset, the systematic biases in simulations and the substantial effect of lateral boundary conditions on the performance of the regional model have also been identified in many other studies (de Elia et al., 2008; Eum et al., 2012).

While the small differences in precipitation are acceptable, the air temperature uncertainties play an especially important role in the hydrological simulations. In the FRB, air temperature controls summer water availability, making regional snowpacks more vulnerable to temperature-induced effects, rather than precipitation. Thus uncertainties in air temperatures are more crucial for hydrological simulations over the FRB rather than those in precipitation.

3.3 Uncertainty in Calibration Optimizer

We further investigate the uncertainty in the optimization of parameters during the calibration process. Many studies have evaluated the parameter uncertainties by adding random noise to the calibration parameters. We use different approach by estimating the uncertainty in the MOCOM-UA optimizer used in the calibration of parameters. This is to estimate the optimizer uncertainty during the VIC calibration process using different values of initial parameters limits. The optimization process for the

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OPT1, OPT2 and OPT3 experiments required 82, 115 and 45 iterations, respectively, to optimize the b_inf, Ds, Ws, D2, D3 and Dsmax parameters to their final values (Fig. 8a-f, Table 3). The corresponding mean monthly (as the optimizer cannot utilize daily data) runoff for the Fraser River at Hope in the OPT1, OPT2 and OPT3 experiments are quite different when compared to observations (Fig. 8g). The NSE scores reveal different accuracy for the three simulations even when the parameters' initial range in the OPT1 and OPT3 experiments is a subset of the OPT2 experiment. The optimization process for parameter calibration would require an expert's experience to set the initial parameter range to converge them to their optimal values. Note that if the initial parameter uncertainty distribution is set as wide as it is physically meaningful, then the optimization will require more computational time to converge toward the Pareto optimum. However, to set the initial parameter limits, the subjective judgement and skill based on experience is needed.

While we perform many sets of experiments with different initial parameters, only OPT1's initial limits produce higher NSE and utilized less computational time. The estimation of hydrologic model parameters depends significantly on the availability and quality of the precipitation and observed streamflow data along with the accuracy of the routing model used. It is therefore important to consider bias correction of forcing datasets as part of automatic calibration. The observed streamflow data used to calibrate the model are often based on water levels that are converted to discharge by the use of a rating curve, which can also induce uncertainty in the observed discharge data.

3.4 Uncertainty in calibration due to PDO Phases

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The FRB's streamflow varies from year to year as well on decadal timescales depending on the timing and magnitude of precipitation and air temperatures during the preceding winter and spring. Given that the FRB air temperature and precipitation is influenced by cool and warm phases of the PDO (Mantua et al., 1997; Fleming et al., 2007; Whitfield et al., 2010; Thorne and Woo, 2011), the choice of VIC calibration and validation periods may induce uncertainty in calibration. The influence of PDO phases in the forcing dataset can produce different snowpack and runoff levels in the hydrological simulation (Supplementary Fig. 7). The long term UW-VIC simulations (1949-2006) show higher mean SWE and runoff levels in a cool PDO phase (1949-1976) and lower mean values in a warm PDO phase (1979-2006). The interannual variations show earlier peak flows characterized by a warm PDO, in response to warmer basin conditions, increased rainfall, and earlier snowmelt. The VIC model calibrations may be biased towards hydrologic conditions of the warm and cold PDO phases and may induce uncertainties in the results. The model performance could be improved by calibrating and validating the model in the same PDO phase (experiments PDO1 and PDO2), i.e. the NSE coefficient is similar in the calibration and validation periods (Table 3). If the calibration is performed in the cool PDO phase and validation in the warm PDO phase (experiment PDO3), the NSE score decreases to 0.79 for the validation period since the model calibration is biased towards the cool conditions, simulating higher flows for the Fraser River at Hope owing to more snow and later snowmelt. For each set of calibration experiments, the calibration parameters are different, which affects the air temperature lapse rates and thus evapotranspiration, the formation of the snowpack, and the timing of snowmelt. Figure 9 shows observed and simulated runoff for the Fraser River at Hope revealing lower observed peak flows ~2.70 mm day^{-1} in a warm PDO phase (PDO1) and higher peak flows ~3.30 mm day^{-1} in a cool PDO phase

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(PDO2). Interestingly the UW driven PDO simulations underestimate peak flows in the warm PDO phase and overestimate them in the cool PDO phase whereas the NSE coefficient for both the cool and warm PDO phases is almost equivalent (Table 4).

We repeat the PDO experiments using the PCIC forcing dataset to compare UW and PCIC simulations under PDO phases. The PCIC PDO simulation shows better agreement with observed data in both cool and warm phases of the PDO compared to the UW PDO simulations. Consistent with UW PDO3 simulation, PCIC PDO3 simulation shows poor performance during validation periods if the calibration is performed in a cool PDO phase (Fig. 9 e, f).

4. Conclusions

This study utilized ANUSPLIN, NARR, UW and PCIC observation-based gridded datasets to evaluate systematic inter-datasets uncertainties and their VIC simulated hydrological response over the FRB. The uncertainties involved in the optimization of model parameters and model calibration under cool and warm phases of the PDO are also examined.

The air temperature in the PCIC and UW datasets were comparable while the PCIC precipitation remains quite high in the Rocky Mountains compared to the UW and NARR datasets. The ANUSPLIN precipitation forcing had a considerable dry bias over mountainous regions of the FRB compared to the NARR, UW and PCIC datasets. The NARR winter air temperature was 2°C warmer than the other datasets over most of the FRB. The PCIC-VIC and UW-VIC simulations had higher NSE values and more reasonable hydrographs compared with observed flows for the Fraser River at Hope. Their performance for many of the FRB's major sub-basins remained satisfactory. The PCIC-VIC simulation

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revealed higher SWE compared to other datasets, probably due to its higher precipitation amounts. The ANUSPLIN-VIC simulation had considerably lower runoff and NSE values along with less SWE and snowmelt amounts owing to its reduced precipitation. The NARR dataset showed warm winter air temperatures, which influenced its hydrological response by simulating less SWE and decreased snowmelt, and hence lower runoff. The trend analysis further highlighted uncertainties of the NARR dataset.

The elevation dependence of maxSWE showed disagreements over the higher elevations of the Rocky Mountains between simulations where the PCIC-VIC simulation overestimate SWE and ANUSPLIN-VIC resulted in underestimation. Furthermore the elevation dependent variation of the maxSWE-day fluctuates considerably between simulations.

The parametric uncertainty in the VIC calibration process reveals that the choice of the initial parameter range plays a crucial role in defining the model performance. During the PDO phases, choice of the calibration and validation time periods play a crucial role in defining the model hydrological response for the FRB. Model calibration was biased towards hydrologic conditions of the warm and cold PDO phases. The UW-VIC PDO simulations underestimated and overestimated the peak flows in the warm and cool PDO phases, respectively.

This study's inter-comparison revealed spatial and temporal differences amongst the ANUSPLIN, NARR, UW and PCIC datasets over the FRB, which is essential to capture the uncertainties in modelling hydrologic responses. Overall, the PCIC and UW datasets had reliable results for the FRB snow hydrology whereas the ANUSPLIN and NARR datasets had issues with either precipitation or

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with air temperature. The FRB's snow-dominated hydrology and its complex elevation profile require highly accurate meteorological station densities to increase the reliability of the high resolution gridded datasets. Improving the quality of precipitation data may thus lead to more accurate hydrological responses in the FRB. There is the need for concrete methods to deal with the increasing uncertainty associated with the models themselves, and with the observations required for driving and evaluating the models.

In this study, the FRB hydrological response considerably varied under different forcing datasets, modelling parameters and remote teleconnections. However there are other sources of uncertainties not discussed here that may establish a range of possible impacts on hydrological simulations. First, the hydrological model used in this study runs at a daily time step, which can be increased to hourly to refine the model performance. The uncertainties in the VIC model structure include here the lack of the representation of glaciers in the current version of the model. Along with these, the VIC simulations are also affected by intrinsic uncertainties in its parameterizations such as, for example, the representation of cold processes (e.g., snowpacks and soil freezing). Such structural uncertainties need to be evaluated by examining multiple hydrological models over the same region. The in situ soil moisture observations that are not necessarily representative of the model grid scale may also contribute to the overall uncertainties in the results. Finally, hydrological simulations are mainly validated using comparisons between simulated and observed flows, which depend on routing models that may contain structural uncertainties. Our future work will investigate such uncertainties using high temporal and spatial resolution hydrological models over the FRB.

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Ziegler, A. D., Sheffield, J., Maurer, E. P., Nijssen, B., Wood, E. F. and Lettenmaier, D. P.: Detection of intensification in global- and continental-scale hydrological cycles: Temporal scale of evaluation, J. Clim., 16(3), 535–547, doi:10.1175/1520-0442(2003)016<0535:DOIIGA>2.0.CO;2, 2003.

Table 1: Description of VIC inter-comparison experiments performed using observational forcings.

VIC model Driving data	Time Span	Ensemble Runs	VIC configuration	Description
The Canadian Precipitation Analysis and the thin-plate smoothing splines (**ANUSPLIN**, Hopkinson et al., 2011)	1979-1990 (Cal.) 1991-2006 (Val.)	5	Domain = 48°– 55°N and 119°–131°W Resolution = 25 km × 25 km, Time Step = Daily Soil Layers = 3 Vertical elevation bands = 10	Validation runs are initiated 5 times with different initial conditions.
North American Regional Reanalysis (**NARR**, Mesinger et al., 2006)				
Pacific Climate Impacts Consortium (**PCIC**, Shrestha et al., 2012)				
University of Washington (**UW**, Shi et al., 2013)				

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Table 2: Performance metrics for the VIC inter-comparison runs. Calibration (1979–1990) and validation (1991–2006) for Fraser River main stem at Hope, BC is evaluated using the Nash–Sutcliffe Efficiency (NSE) coefficient and correlation coefficient (r, all statistically-significant at $p < 0.05$).

Experiments	1979-1990 Calibration		1991-2006 Validation	
	NSE	r	NSE	r
ANUSPLIN	0.54	0.91	0.55	0.94
NARR	0.67	0.85	0.81	0.90
PCIC	0.90	0.96	0.90	0.95
UW	0.82	0.94	0.80	0.92

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Table 3: Parameters used to optimize during the calibration process for mean daily runoff for the Fraser River at Hope. OPT1, OPT2 and OPT3 are different experiments using same forcing data but with different initial range for each calibration parameter.

VIC model Calibration Parameters *(units)*	Description	Initial Range (Final Optimized Parameters)		
		Experiment OPT1	Experiment OPT2	Experiment OPT3
b_inf	Controls the partitioning of precipitation (or snowmelt) into surface runoff or infiltration	0.2-0.00001 **(0.14)**	0.3-0.00001 **(0.23)**	0.25-0. 10 **(0.23)**
Ds	Fraction of maximum baseflow velocity	0.1-0.000001 **(0.05)**	0.9-0.00001 **(0.27)**	0.30-0.04 **(0.23)**
Ws	Fraction of maximum soil moisture content of the third soil layer at which nonlinear baseflow occurs	0.6-0.20 **(0.28)**	1.0-0.1 **(0.61)**	0.65-0.20 **(0.43)**
D2 *(m)*	The second soil layer thicknesses, which affect the water available for transpiration	1.0-0.7 **(0.72)**	3.0-0.7 **(0.71)**	0.80-0.70 **(0.74)**
D3 *(m)*	The third soil layer thicknesses, which affect the water available for baseflow	2.5-0. 7 **(1.60)**	5.5-0.7 **(1.35)**	2.00-1.00 **(1.45)**
Dsmax *(mm day^{-1})*	Maximum baseflow velocity	18.0-12.0 **(13.66)**	30.0-12.0 **(22.48)**	23.0-12.0 **(16.41)**

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Table 4: Performance metrics for the UW forcing driven PDO runs. Calibration and validation for Fraser River main stem at Hope, BC is evaluated using the NSE coefficient using the dataset. See text for the detail of PDO experiments.

Experiment Name	Calibration		Validation	
	NSE	PDO Phase	NSE	PDO Phase
PDO1	0.84 **1981-1990**	Warm (low flows)	0.84 **1991-2001**	Warm (low flows)
PDO2	0.84 **1956-1965**	Cool (high flows)	0.85 **1966-1976**	Cool (high flows)
PDO3	0.84 **1967-1976**	Cool (high flows)	0.79 **1977-1987**	Warm (low flows)

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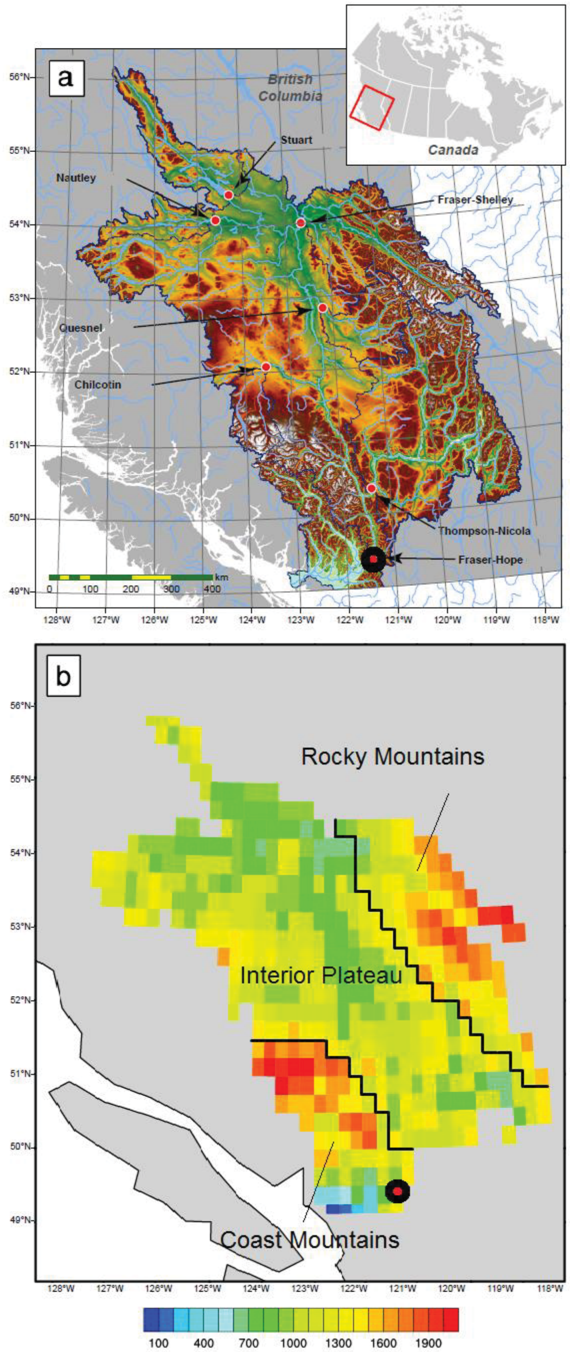

Figure 1: (a) High-resolution digital elevation map of the FRB with identification of major sub-basins including the Fraser River main stem at Hope, BC. (b) FRB mean elevation (m) per VIC model gridcell. The Fraser River main stem at Hope is highlighted in both plots as black circle.

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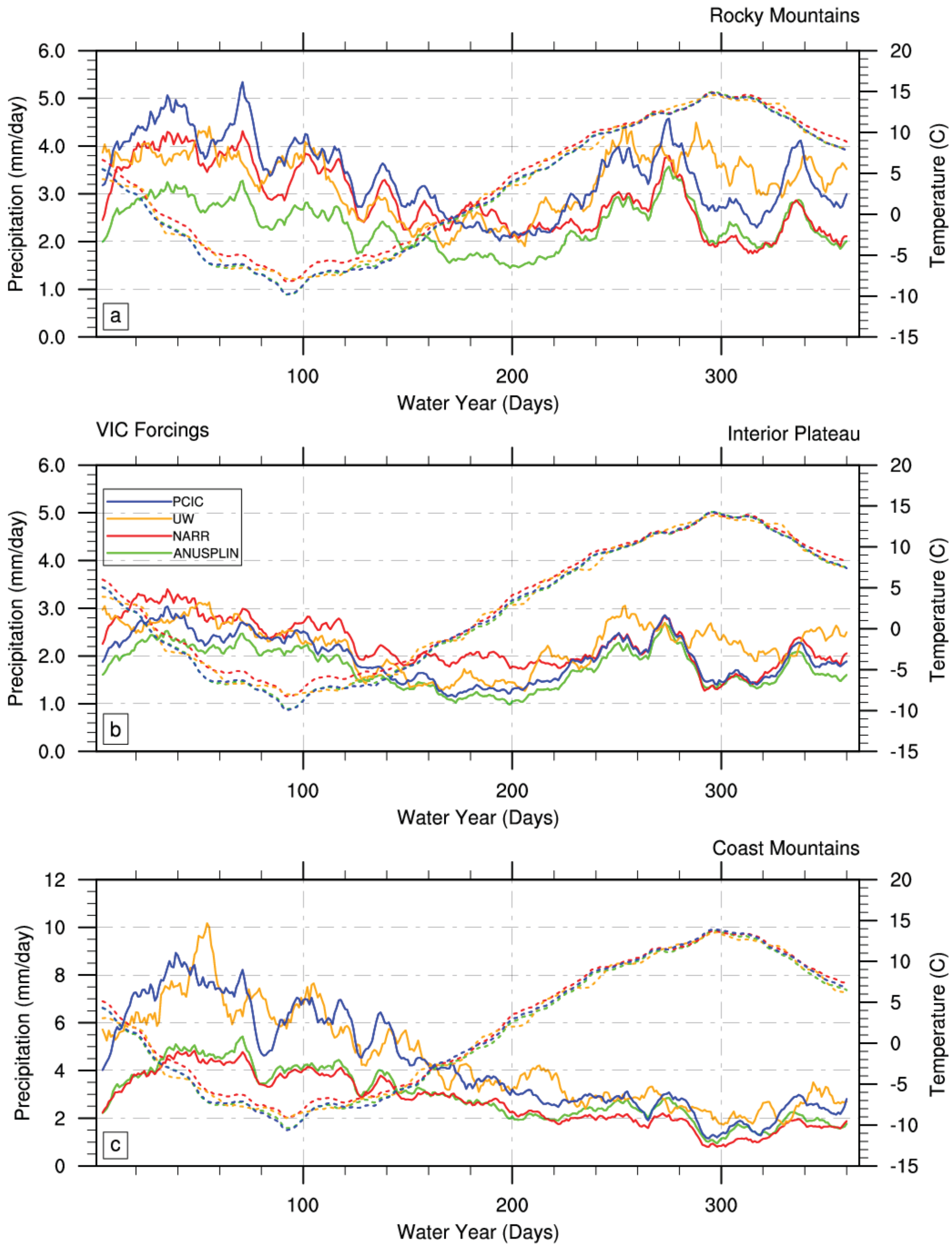

Figure 2: Area-averaged time series of mean daily air temperature (dotted lines) and daily precipitation (solid lines) over the (a) Rocky Mountains, (b) Interior Plateau, and (c) Coast Mountains for the ANUSPLIN, NARR, UW and PCIC forcing datasets, water years 1979-2006.

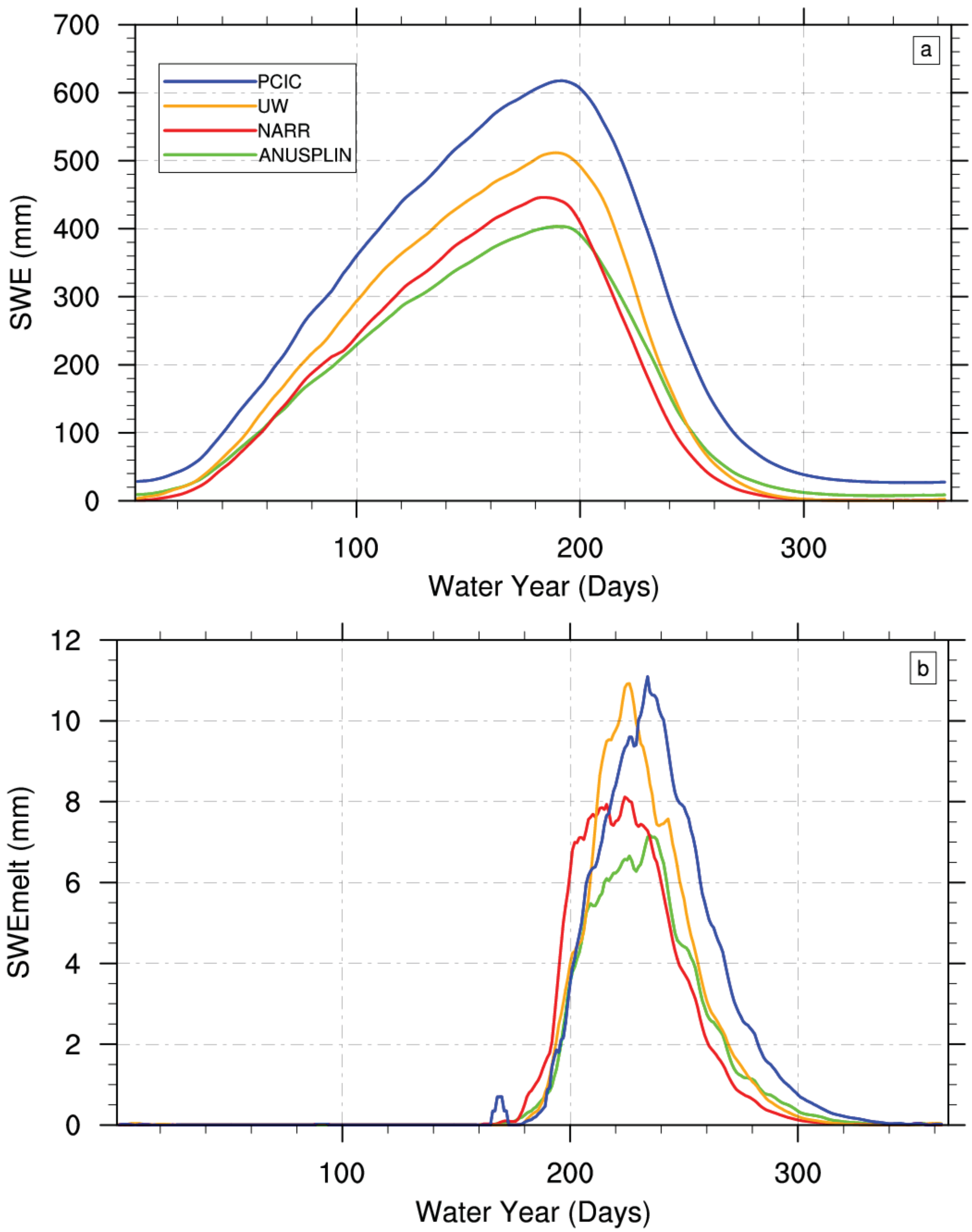

Figure 3: Area-averaged time series of daily mean (a) SWE and (b) SWEmelt for the ANUSPLIN-VIC, NARR-VIC, UW-VIC and PCIC-VIC simulations averaged over the Rocky Mountains, water years 1979-2006.

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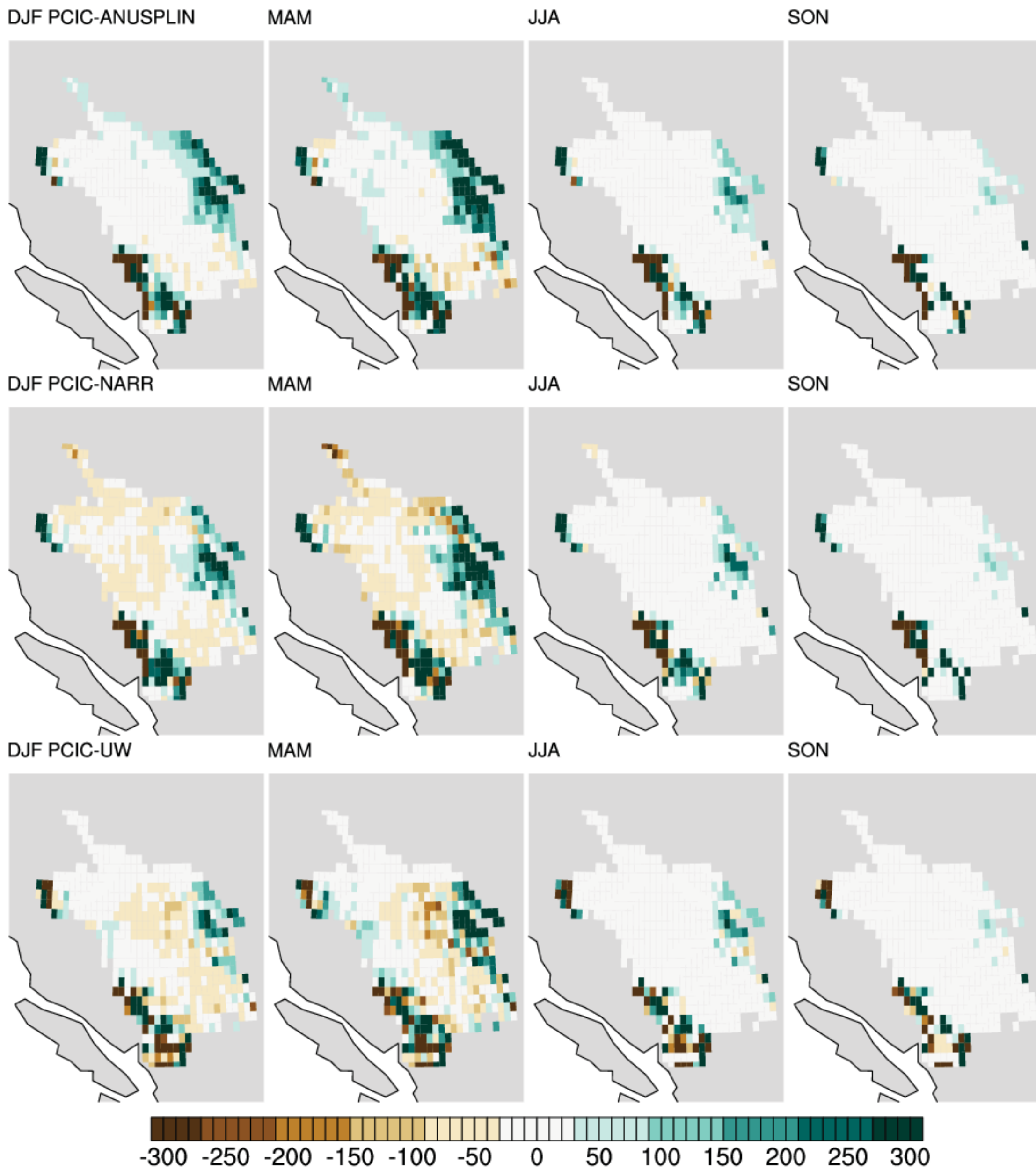

Figure 4: Spatial differences of mean SWE (mm) based on PCIC-VIC minus ANUSPLIN-VIC (1st row), NARR -VIC (2nd row) and UW (3rd row) simulations, water years 1979-2006. DFJ, MAM, JJA and SON correspond to winter, spring, summer and autumn, respectively.

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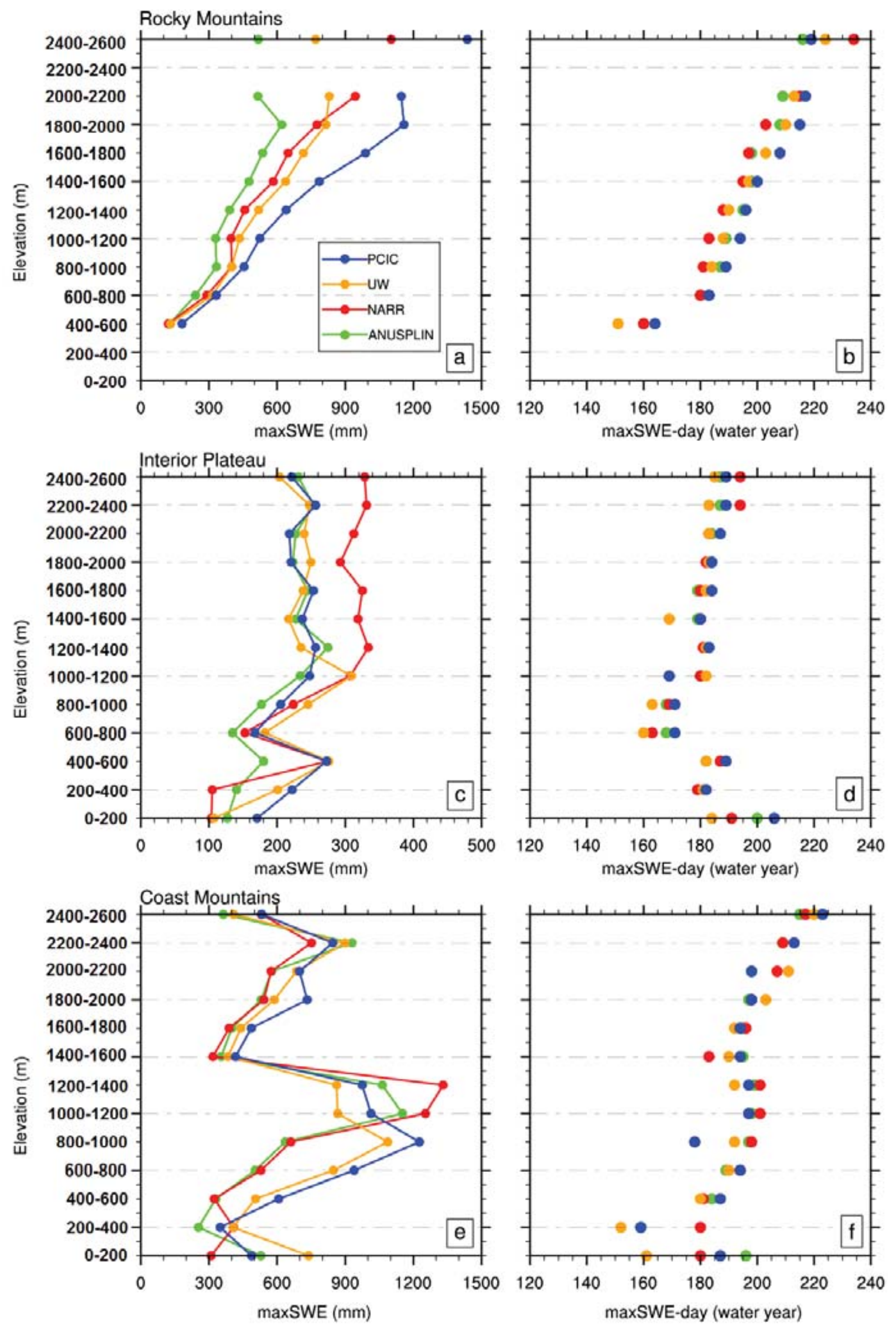

Figure 5: Variation of (a, c, e) maxSWE and corresponding (b, d, e) maxSWE-day for the ANUSPLIN-VIC, NARR-VIC, UW-VIC and PCIC-VIC simulations averaged over (a, b) Rocky Mountains, (c, d) Interior Plateau and (e, f) Coast Mountains, water years 1979-2006.

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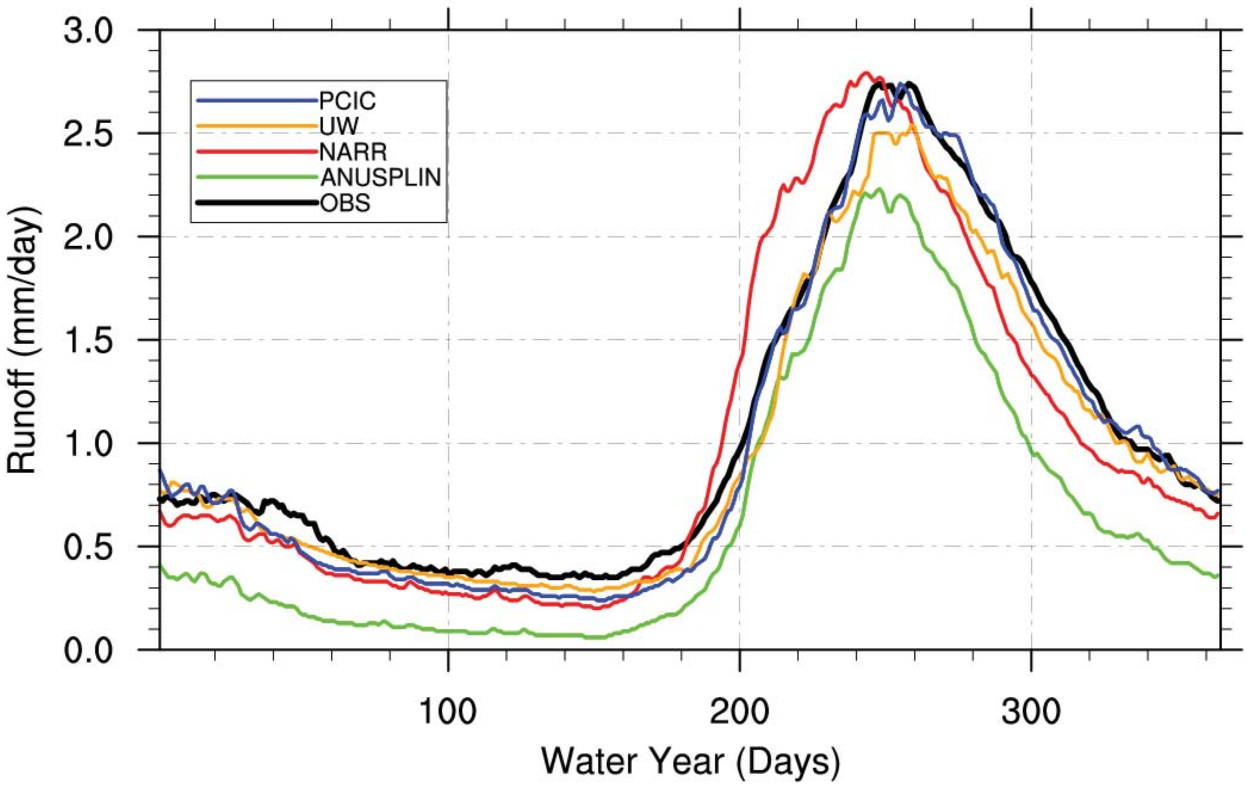

Figure 6: The simulated and observed daily runoff for the Fraser River at Hope averaged over water years 1979-2006. An external routing model is used to calculate runoff for the ANUSPLIN-VIC, NARR-VIC, UW-VIC and PCIC-VIC simulations.

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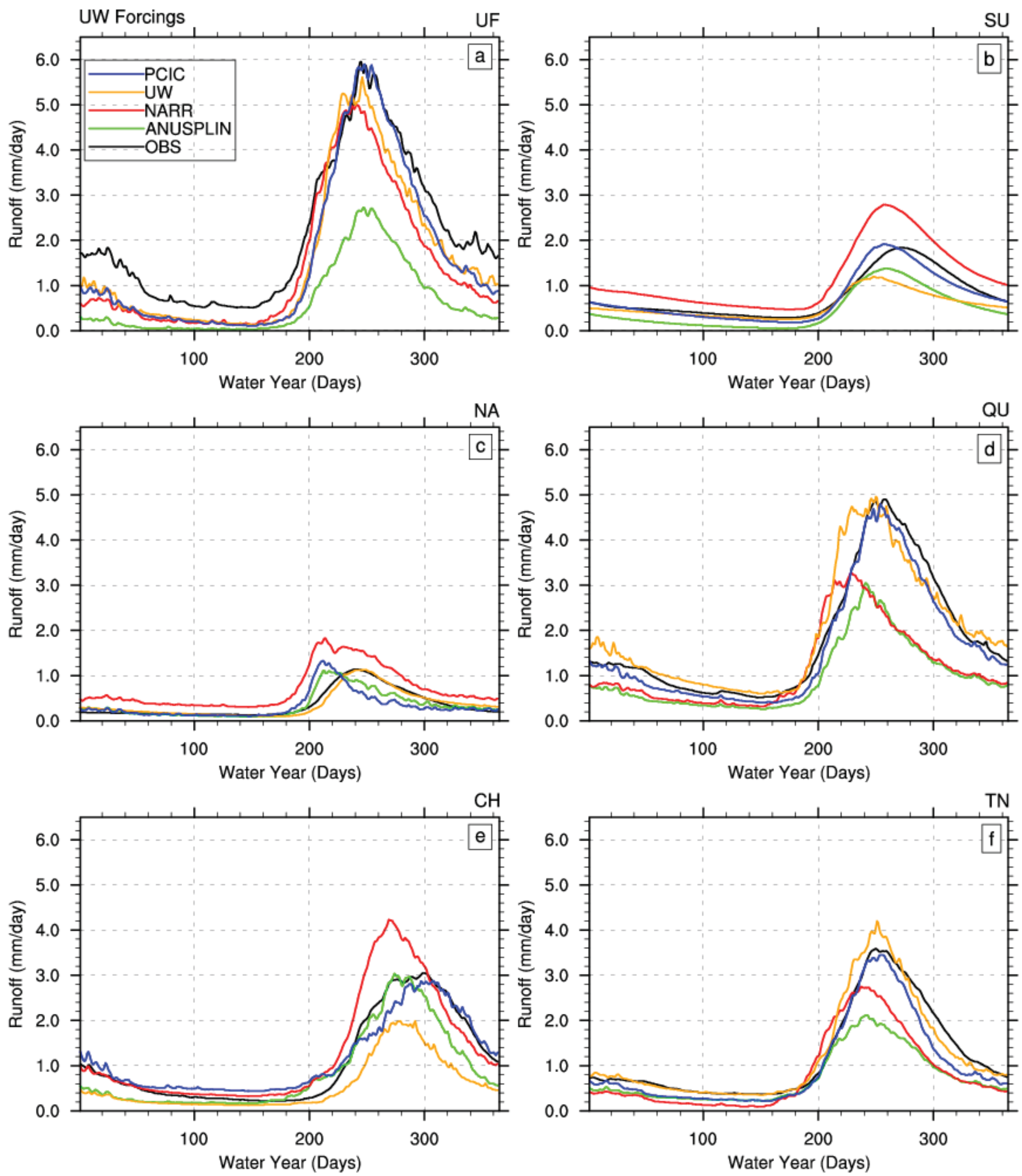

Figure 7: Same as Figure 6 but for FRBs six major sub-basins.

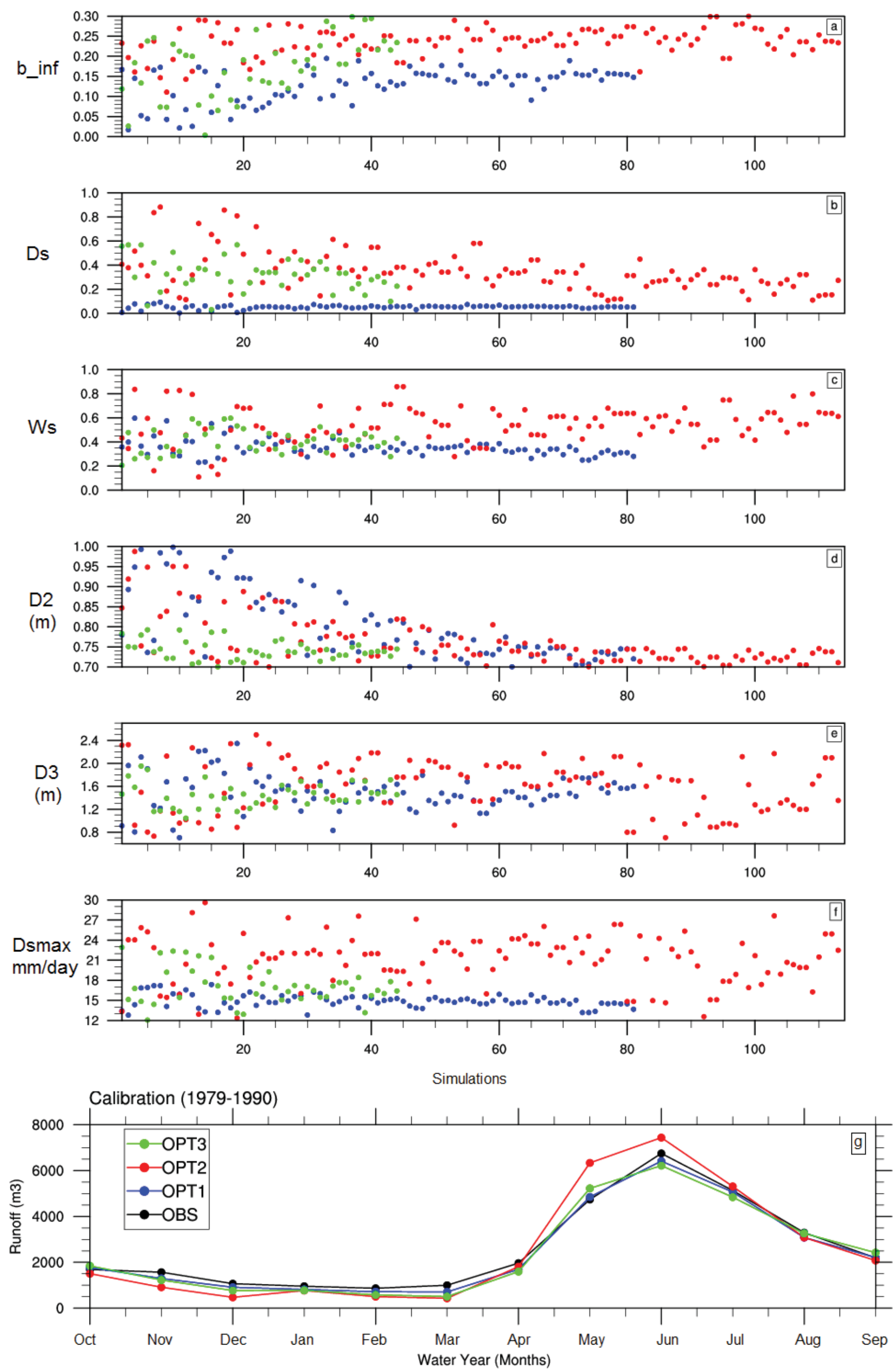

Figure 8: (a-f) Optimization of three different sets of calibration parameters using MOCOM-UA optimizer. The parameter estimates converge toward the Pareto optimum using the MOCOM-UA calibration algorithm for (a) b_inf, (b) Ds, (c) Ws, (d) D2, (e) D3 and (e) Dsmax. (g) VIC simulations using three different parameter sets (labelled as OPT1, OPT2 and OPT3, see text and Table 3 for details) are compared for mean monthly runoff for the Fraser River at Hope.

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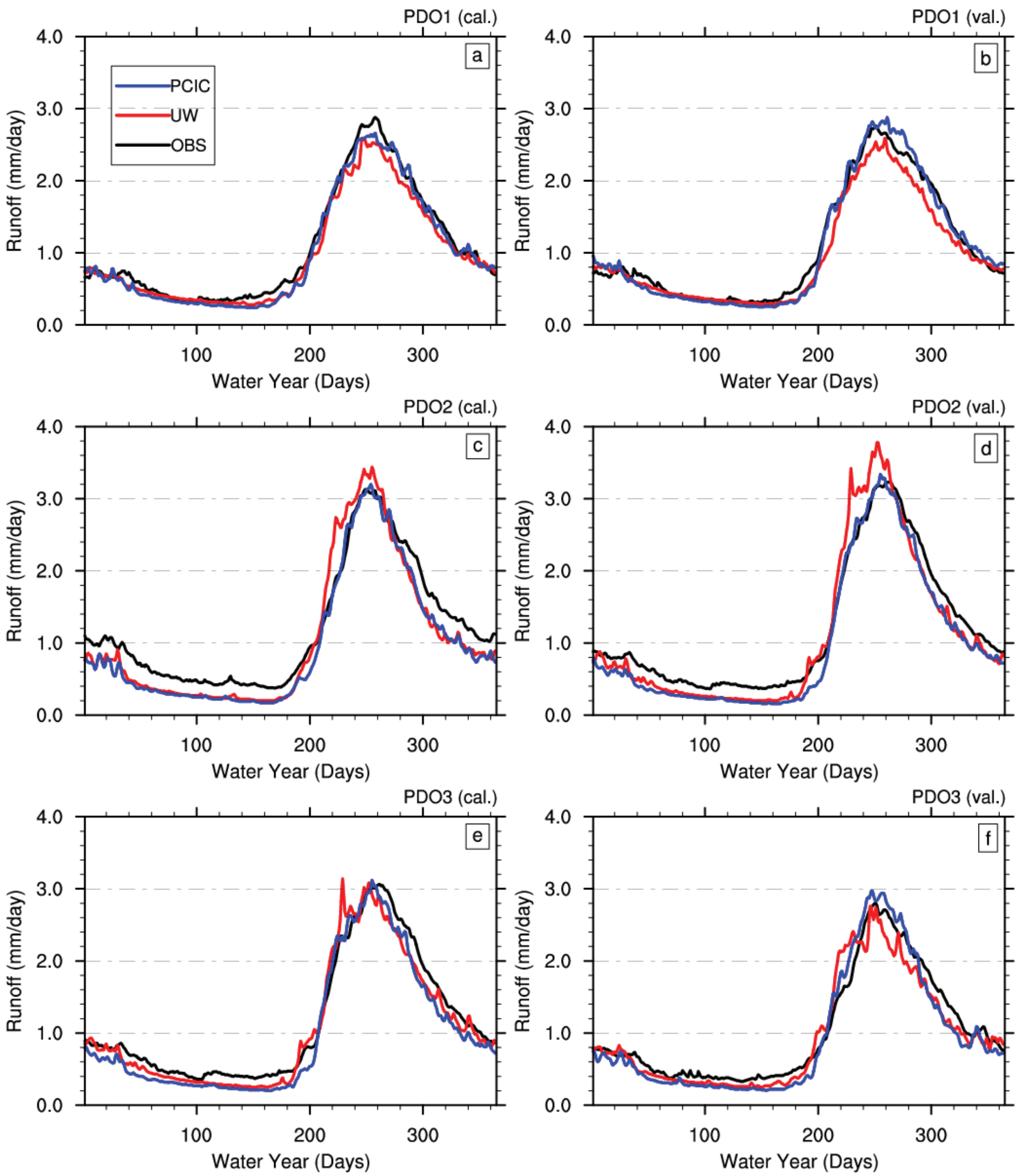

Figure 9: Daily runoff during calibration (cal.) and validation (val.) under different PDO phases for the Fraser River main stem at Hope, BC. PDO1 (cal. 1981-1990 val.1991-2001), PDO2 (cal. 1956-1965 val.1966-1976) and PDO3 (cal. 1967-1976 val.1977-1987) refer to VIC experiments performed during warm, cool and cool/warm PDO phases (see text and Table 4 for details).