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Publication Date

2016

DOI

10.1016/j.advwatres.2015.10.007

Advances in Water Resources 87 (2016) 42–55

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Seasonal flows of international British Columbia-Alaska rivers: The nonlinear influence of ocean-atmosphere circulation patterns

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ARTICLE INFO

Article history:
Received 18 July 2015
Revised 13 October 2015
Accepted 14 October 2015
Available online 22 October 2015

Keywords:
Hydroclimatology
Streamflow
ENSO
Arctic Oscillation
Pacific Decadal Oscillation
North Pacific Gyre Oscillation

ABSTRACT

The northern portion of the Pacific coastal temperate rainforest (PCTR) is one of the least anthropogenically modified regions on earth and remains in many respects a frontier area to science. Rivers crossing the northern PCTR, which is also an international boundary region between British Columbia, Canada and Alaska, USA, deliver large freshwater and biogeochemical fluxes to the Gulf of Alaska and establish linkages between coastal and continental ecosystems. We evaluate interannual flow variability in three transboundary PCTR watersheds in response to El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Arctic Oscillation (AO), and North Pacific Gyre Oscillation (NPGO). Historical hydroclimatic datasets from both Canada and the USA are analyzed using an up-to-date methodological suite accommodating both seasonally transient and highly nonlinear teleconnections. We find that streamflow teleconnections occur over particular seasonal windows reflecting the intersection of specific atmospheric and terrestrial hydrologic processes. The strongest signal is a snowmelt-driven flow timing shift resulting from ENSO- and PDO-associated temperature anomalies. Autumn rainfall runoff is also modulated by these climate modes, and a glacier-mediated teleconnection contributes to a late-summer ENSO-flow association. Teleconnections between AO and freshet flows reflect corresponding temperature and precipitation anomalies. A coherent NPGO signal is not clearly evident in streamflow. Linear and monotonically nonlinear teleconnections were widely identified, with less evidence for the parabolic effects that can play an important role elsewhere. The streamflow teleconnections did not vary greatly between hydrometric stations, presumably reflecting broad similarities in watershed characteristics. These results establish a regional foundation for both transboundary water management and studies of long-term hydroclimatic and environmental change.

1. Introduction

Climate variability has important implications for water resource management because temperature and precipitation variations alter surface water availability at the basin scale. Broadly speaking, changes in streamflow directly impact water resources and also have a variety of indirect impacts on riverine ecosystem services, such as recreation and fish habitat. In basins that experience large interannual variations in hydroclimatic drivers, year-to-year variability in streamflow can be pronounced (e.g., [14]). Such variability complicates the precise management of water resources, particularly in basins where demands on water resources are increasing [67].

Managing water resources in the face of hydroclimatic variability has the potential to be especially challenging in transboundary watersheds, which cover just under half of the global land surface and affect about 40% of the world's population [80]. As discussed in detail by Wolf [80], the runoff from these basins provides a critical, non-substitutable resource that flows and fluctuates across time and space, yet overall, this resource is becoming scarcer as both populations and standards of living grow, and the effective allocation of transboundary water resources requires international cooperation by management agencies operating within an often-vague legal framework. In North America, the history of international water management provides clear examples of the advantages of understanding and anticipating basin-scale hydroclimatic variability – and also the consequences of failing to do so. For example, climate-based seasonal water supply forecasting can increase yearly hydroelectric

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http://dx.doi.org/10.1016/j.advwatres.2015.10.007
0309-1708/Published by Elsevier Ltd.

production revenue on the transboundary (Canada–US) Columbia River by hundreds of millions of dollars [27], and operational forecast models in that region now use such climate-informed methods routinely (e.g., [25]). Conversely, the Colorado River Compact, based on a short record of early twentieth-century instrumental observations that was later discovered to represent a period of anomalously high flow in the US southwest, led to water supply over-allocations so severe that the river now barely runs to its mouth across the international border in Mexico (e.g., [11,52,74]).

While there is clearly potential for cross-border disagreements over water, the environmental policy and management literature suggests that water conflicts are surprisingly rare, especially at the international level (e.g., [6,80]). Transboundary rivers flowing between British Columbia (BC), Canada and Alaska (AK), United States are currently at particularly low risk of any such disagreements. Canada and the US are good neighbors with a long history of effective joint management of shared basins. The Boundary Waters Treaty of 1909 and Columbia River Treaty of 1964 and their associated institutions, such as the International Joint Commission, provide evidence of these successful relationships. Furthermore, the wet climate and low population levels of the BC-AK border region currently result in negligible water stress. That said, human activities, such as tourism, mining, and commercial and recreational fisheries, including in particular the iconic salmon runs of the west coast, are all of central importance here and are closely related to the availability of abundant fresh water. Some of these activities may be expanding, as are the human populations of both British Columbia and Alaska. In this context, developing a better understanding of interannual variations in transboundary river flows in the BC-AK region will facilitate the early development of a positive water management framework, which is a tenet of successful international water management (e.g., [80]). Such understanding would also aid the joint planning and management process of climate adaptation.

Understanding the hydroclimatic controls on freshwater discharge from transboundary rivers in this region also has important implications for a rich diversity of physical and ecological processes. The Pacific coastal temperate rainforest (PCTR) ecosystem extends 4000 km along the west coast of North America, from northern California to Kodiak Island, Alaska [37]. The northern portion, located principally in central and southeast Alaska and northern British Columbia, remains one of the least anthropogenically modified ecosystems on Earth, home to intact old-growth forests, extensive alpine glaciers and icefields, robust wild fisheries, and many resource- and tourism-based communities [64]. The BC-AK border region covers an approximate 1000-km long swath of the northern PCTR. River flow regimes here reflect autumn-winter precipitation and summertime temperature maxima, and a consequent mixture of autumn rain-driven river flows, spring-summer snowmelt-driven runoff, and late-summer glacier melt. Streamflow is also dependent on individual basin properties including hypsometry, microclimate and land surface properties. River flow variability here influences the strength of density-driven coastal currents (e.g., Alaska Coastal Current [72]) and spawning migration survival of transboundary salmon runs (e.g., [26]). Additionally, runoff from these basins into the Gulf of Alaska (GOA), which typically exceeds 150 km^3 year^{-1} [31,57,60], has the potential to be substantially altered by changes in regional glacier volume [10,42,43] and shifts in the rain/snow fraction of winter precipitation [61,73]. Such climate-driven hydrological variability propagates downstream into coastal marine ecosystems, and the corresponding suite of terrestrial, aquatic, and marine environmental effects are likely to be profoundly seasonal [64].

Our goal is to develop a baseline understanding of how the seasonal flow patterns of transboundary British Columbia-Alaska rivers vary interannually under the influence of climatic drivers. While long-term shifts in mean state are important, including those potentially associated with projected anthropogenic climate changes, it is the year-to-year variation in water supply that often has the largest impacts on ecosystems and for natural resource managers (e.g., [65,67]). This is evident, for example, in the 2013–2015 California drought, which primarily reflects precipitation variations that appear to fall within the envelope of historical variability and processes [49], yet which have caused tremendous water management challenges. Near the BC-AK region, the interannual variability in freshwater discharge into the GOA regularly exceeds 20% due mainly to shifts in precipitation and glacier volume loss rates [31]. Understanding historical flow variability is a crucial first step toward rigorously predicting how watersheds may respond to longer-term climatic shifts, as an accurate portrayal of variability is essential to resolving unaliased trends in a region where hydrologic variability exceeds trend [63]. Characterizing the major modes of variation in the seasonal flows of BC-AK rivers therefore represents a priority from the perspective of developing a sound scientific basis for international water and ecosystem management.

Doing so can be daunting. The coupled ocean-atmosphere system, which provides the primary input signal to watershed hydrologic systems, is massively complex and varies on spatial scales ranging from microscopic to global, and temporal scales ranging from seconds to millennia. Fortunately, ocean-atmosphere dynamics tend to self-organize into coherent patterns. This feature of the climate system is widely capitalized upon in hydrology and many other disciplines as a convenient framework for assessing climate variability impacts (e.g. [18,24,50]). Teleconnections to such climate modes have, with the possible exception of the Pacific Decadal Oscillation, enjoyed relatively little scrutiny in southeast Alaska and northwest British Columbia in comparison to other areas of western North America and, indeed, even other areas of Alaska and British Columbia. Nonetheless, prior teleconnection analyses within and near this border region (e.g., [4,5,16,20,32,48,61]) provide encouraging signs that this should be a fruitful approach to conceptualizing and characterizing the interannual streamflow variability of transboundary rivers in the area.

In this study, we analyzed long-term observational streamflow data from four hydrometric stations on three international rivers straddling the BC-AK border, as well as selected climate station data, in the context of four ocean-atmosphere patterns that seem particularly likely to influence streamflow in this region. The emphasis lies with identifying seasonal relationships of water resources to ocean-atmosphere circulation indices. We then explore climate station data to understand some of the regional hydroclimatic mechanisms for these streamflow teleconnections, and briefly consider some of the implications of the hydrological results to water supply forecasting, regional ecology and salmon habitat, and longer-term climate changes. The suite of statistical methods employed, which include both nonparametric and information theoretic techniques, were chosen to facilitate assessment of both seasonally transient and highly nonlinear teleconnections, reflecting the strongly seasonal nature of hydrometeorological processes in the region and the widespread consensus that many such climatic associations are nonlinear, in some cases strongly so. Our findings represent the first focused assessment of streamflow teleconnections for international Canada–US rivers along the BC-AK border.

2. Data and methods

The BC-AK border generally follows the crest of the Coast Mountains, which separate colder, drier interior areas from the much milder and wetter coast. This boundary also roughly corresponds to a surface water drainage divide. However, the mainland portion of the Alaskan panhandle can be only a few tens of kilometers wide, and the larger rivers tend to penetrate the Coast Mountains into the interior, spanning the international border. Most of the region is highly remote, and as a consequence, relatively few transboundary BC-AK rivers have enjoyed long-term hydrometric monitoring,

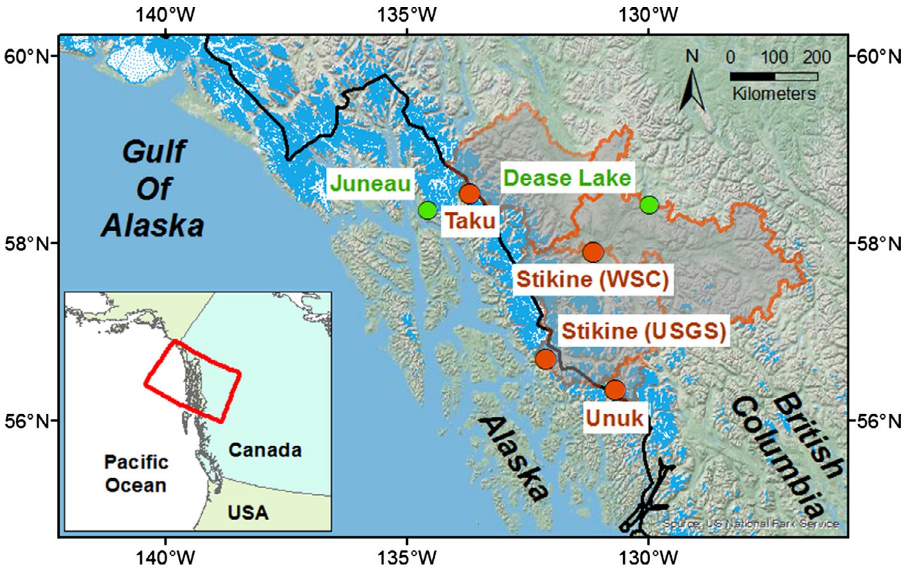

Fig. 1. Location map, spanning the entirety of the Alaskan panhandle. Thick black line denotes international boundary. Orange and green symbols give locations of hydrometric and climate stations, respectively. Orange outlines and gray shading denote corresponding watershed areas. Light blue outlines and stippling indicate ice-covered area from the GLIMS Randolph Glacier Inventory [1].

Table 1
Summary of hydrologic and climate monitoring stations used. ID is the USGS or NOAA (US) or WSC or MSC (Canada) station code, as appropriate. *N* is number of years of data employed in the analysis (for Dease Lake, this differs slightly between AHCCD *T* and *P* records). *TAP* is the total annual precipitation (mm) averaged over that period of record, *MAT* is mean annual temperature (°C), and Q_{ave} is annual mean flow (m^3/s). *A* is basin area upstream from the gauge ($\times 10^3$ km^2), and A_g is the proportion of that area having glacier cover (%), both taken from internal WSC and USGS documentation.

Name	ID	*N*	*TAP*	*MAT*	Q_{ave}	*A*	A_g
Taku	15041200	27	n/a	n/a	387	17.2	8
Stikine (Wrangell)	15024800	38	n/a	n/a	1606	51.8	10
Unuk	08DD001	30	n/a	n/a	105	1.5	40
Stikine (Telegraph Creek)	08CE001	50	n/a	n/a	825	29.0	2
Juneau	PAJN	64	1480	5.2	n/a	n/a	n/a
Dease Lake	1192340	58–62	480	−0.8	n/a	n/a	n/a

resulting in only sparse hydroclimatic datasets from this region (e.g., [31,57,79]).

US Geological Survey (USGS) and Water Survey of Canada (WSC) streamflow databases were screened for hydrometric stations on the main stems of unregulated transboundary BC-AK rivers having about 25 years or more of year-round daily data collection. Four discharge records were deemed suitable for teleconnection analysis (Fig. 1, Table 1). The USGS stations on the Taku River and the Stikine River at Wrangell are not far from tidewater and thus reflect the combined Canadian–American freshwater delivery to the coastal ocean from these two basins (Fig. 1). The WSC station on the Stikine River at Telegraph Creek is located far upstream from the USGS station on the same river, capturing headwater effects (Fig. 1). Unlike the archetypal watershed which flows from wet mountain headwaters to drier lowland plains, the Stikine originates in a high, cold, comparatively dry and flat interior plateau region, then cuts through a tall, very wet, and extensively glacierized coastal mountain range, before emptying into a deep fjord. By flow volume, the Stikine is the largest river along the southeast Alaska coast and among the top 50 globally [45]. The WSC station on the Unuk River approximately reflects Canadian freshwater delivery to the American border (Fig. 1). To facilitate some understanding of the regional hydroclimatic mechanisms whereby large-scale atmosphere-ocean circulation patterns affect the flows of these rivers, we additionally analyzed daily mean temperature and daily total precipitation data from US National Oceanographic and Atmospheric Administration (NOAA) and Meteorological Service of Canada (MSC) long-term surface climate stations at coastal (Juneau International Airport, Alaska) and interior (Dease Lake, BC; adjusted homogenized Canadian climate data, AHCCD) locations [51,75] (Fig. 1, Table 1). Fig. 2 illustrates all the streamflow and climate data used.

The data were organized into hydrologic years (HY), spanning 1 October of one calendar year to 30 September of the next and assigned to the second calendar year. Ideally, a hydroclimatalogical analysis would capture interannual variation in sub-seasonal transient processes, without being biased or contaminated by high-frequency noise, and additionally would fully capture nonlinear hydroclimatic responses. Data assembly and processing were undertaken accordingly. A $(2m+1)$-point binomial filter with $m = 10$ was applied to each daily time series (e.g., [55]). The filter was not run across hydrologic years, so that year-to-year serial correlation was not artificially induced, and the first and last *m* days for a given HY were left unfiltered. Data gaps were not interpolated, and all data within any window position of the filter including a data gap were in turn transformed to data gaps; this conservative approach favors using slightly less data in the analysis over making assumptions during interpolation. The filter gave a 50% response at a timescale of $3m^{1/2}$ $\sim$ 9 days, roughly comparable to the 5-day sequent means used by Whitfield et al. [78] and Déry et al. [13], for example, in hydroclimatic modeling and analysis. This combination of fine sampling interval and low-pass filter thus suppresses very high-frequency noise while maintaining a high seasonal resolution. This high seasonal resolution, which is becoming widely used in hydroclimatological

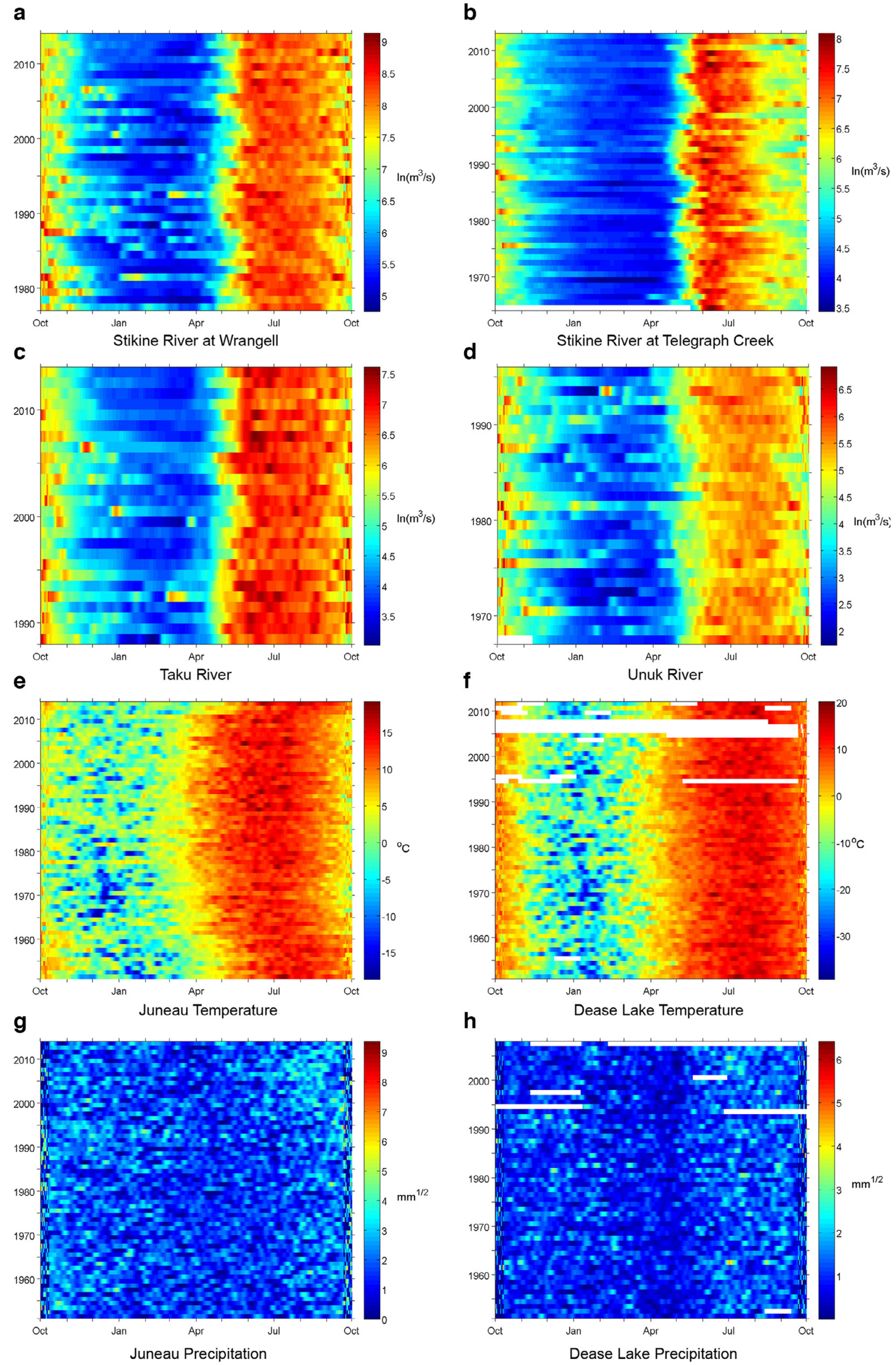

Fig. 2. Hydrometeorological datasets considered. Flow is given as its logarithm and precipitation as its square root for relative ease of visualization, but untransformed values were used in the analyses.

analyses (e.g., [13,19,28,29,78]), facilitates the study of seasonally transient physical hydrologic processes (such as the onset of the spring snowmelt freshet, or late-summer peak glacier meltwater production following exhaustion of the seasonal snowpack), which may last only a few weeks and can be easily obscured in monthly or seasonal averages or totals. It also expedites the identification of nonlinear effects which can similarly be lost to such temporal aggregation [13,34,53,62,66]. Previous work has empirically demonstrated that the specific data processing and analysis methods used here enable detection of statistically and physically significant hydrologic

Table 2
Interpretation key for correlations, R_s, between streamflow, Q, versus a given climate index, ν, and its square, ν^2. A relationship is only taken to exist if the corresponding value of R_s is statistically significant. By a concave-upward parabolic association, for example, we mean a teleconnection such that Q is largest at extreme positive and negative values of the climate index, such as during both extreme El Niño and extreme La Niña events.

R_s (Q,ν)	R_s (Q,ν^2)	Outcome
Positive	None	Linear positive association
Negative	None	Linear negative association
None	Positive	Parabolic association, oriented concave upward
None	Negative	Parabolic association, oriented concave downward
Positive	Positive or negative	Nonlinear positive association
Negative	Positive or negative	Nonlinear negative association
None	None	No association

teleconnections that cannot be identified using more temporally coarse-grained datasets [19]. Our moderate low-pass filtering notwithstanding, the trade-off is in principle a lower signal-to-noise ratio, as we do not enjoy the benefit of the random noise suppression associated with "stacking" processes like seasonal or annual averaging (e.g., [17]).

Standard practice for statistical detection of water resource teleconnections, particularly in the numerous prior studies of snowmelt-influenced rivers in western North America, is to consider the wintertime mean state for the large-scale ocean-atmosphere circulation pattern of interest, and then explore its relationships to local hydrology and climate during the corresponding water year, i.e., that winter and the following spring and summer. Accordingly, we determined December–January–February (DJF) means of the standard indices for several organized patterns of climatic variability. El Niño-Southern Oscillation (ENSO) and the Arctic Oscillation (AO, also known as the Northern Annular Mode) were chosen because they are the dominant modes of interannual atmospheric variability in the Northern Hemisphere [76]. The Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO, closely related to the Victoria Pattern) were selected because they are the leading modes of interannual oceanic variability in the North Pacific [7,15,48]. Unlike the other three patterns, ENSO has several common indices; we chose the Oceanic Niño Index (ONI), used by NOAA for operational purposes (e.g., [41]). For a given climate mode and river, the annual time series of DJF mean index values was correlated against an annual time series of streamflow corresponding to a given day of the water year (e.g., a N-year record of May 12 flow). This was repeated for each day of the year, to form a seasonally high-resolution picture of flow teleconnections across the hydrologic year. The entire process was then completed for all climate modes and hydrometric and climate stations. A two-sided hypothesis test ($p_{crit} = 0.10$) on the Spearman rank correlation coefficient was used, as this method does not require distributional assumptions (e.g., [30]).

The foregoing assessment was additionally performed for the squares of the climate indices. This was done to accommodate outcomes from recent work demonstrating that northern-hemisphere teleconnections can not only be moderately nonlinear, as previously well-recognized (e.g., [22,33,39]), but in fact quadratic, giving a parabolic shape in which opposite extreme climate states (such as El Niño and La Niña) both give a similar local climatic impact [2,18,19,35,81]. These highly nonlinear teleconnection components, which may be the result of quadratic terms in the governing equations for atmospheric circulation [35], can have important repercussions to assessment of hydroclimatic dynamics. One of these implications is the emergence of teleconnections where none had clearly been previously identified, such as strong ENSO effects in the Sacramento Basin of northern California [18,35]. To date, such strongly nonlinear teleconnections have only been identified for ENSO and the AO, but we entertain the possibility that they may be present in the PDO and NPGO as well. Table 2 provides interpretive guidelines for various combinations of correlations against a climate index and its square.

We complemented this Spearman rank correlation analysis with an Akaike Information Criterion (AIC)-based polynomial selection method, as described in Fleming and Dahlke [18]. In summary, the AIC-based approach accommodates no-effect, linear-effect, and (strongly) nonlinear-effect teleconnection models, and it estimates the probability that the model is true given the data. This alternative statistical technique is based on fundamentally different principles than conventional null-hypothesis significance testing, and in this study, it is used to provide a methodologically independent check on the outcomes of the rank correlation analyses by generating estimates of the probability that any plausible teleconnection (either linear or quadratic; see [18,35,81] for details) is present. That is, when a given relationship is supported by both a statistically significant correlation coefficient between flow versus a climate index and/or its square, and also a high probability that a linear or quadratic polynomial relationship exists, greater confidence can be placed in the existence of that hydroclimatic association.

3. Results

We begin by identifying the major streamflow teleconnections for international British Columbia-Alaska rivers, which is the primary aim of this study. We then use climate station data to gain some understanding of the regional meteorological mechanisms whereby large-scale atmosphere-ocean circulation patterns generate these particular water resource teleconnections. The corresponding outcomes are summarized in this section. Some generalizations, comparisons to other work in the BC-AK border region and neighboring areas, and explorations of some of the broader implications of the results are provided in the next section (Section 4).

We focus first on results for ENSO, which showed the most pronounced and coherent impacts on streamflow within the transboundary watersheds examined. We concentrate on phenomena that are consistent across multiple stream gages, readily physically interpretable in terms of associated regional meteorological anomalies, and marked by both statistically significant Spearman rank correlations and AIC-based estimates of the probability of a teleconnection ranging from about 0.8 to 1.0. In the case of ENSO, there are three such hydroclimatic effects, occurring at different times of year (see Fig. 3 and interpretive key in Table 2).

The strongest streamflow teleconnection to ENSO in the three transboundary rivers is a positive ONI-discharge correlation during the rising limb of the freshet, over approximately March–April through May–June depending on the particular location (Fig. 3a–d). The effect is temporally coincident with a positive association between ONI and spring temperature (Fig. 3e and f). That is, the El Niño climate state appears to drive warmer springtime air temperatures and an associated increase in snowmelt in early spring, giving an

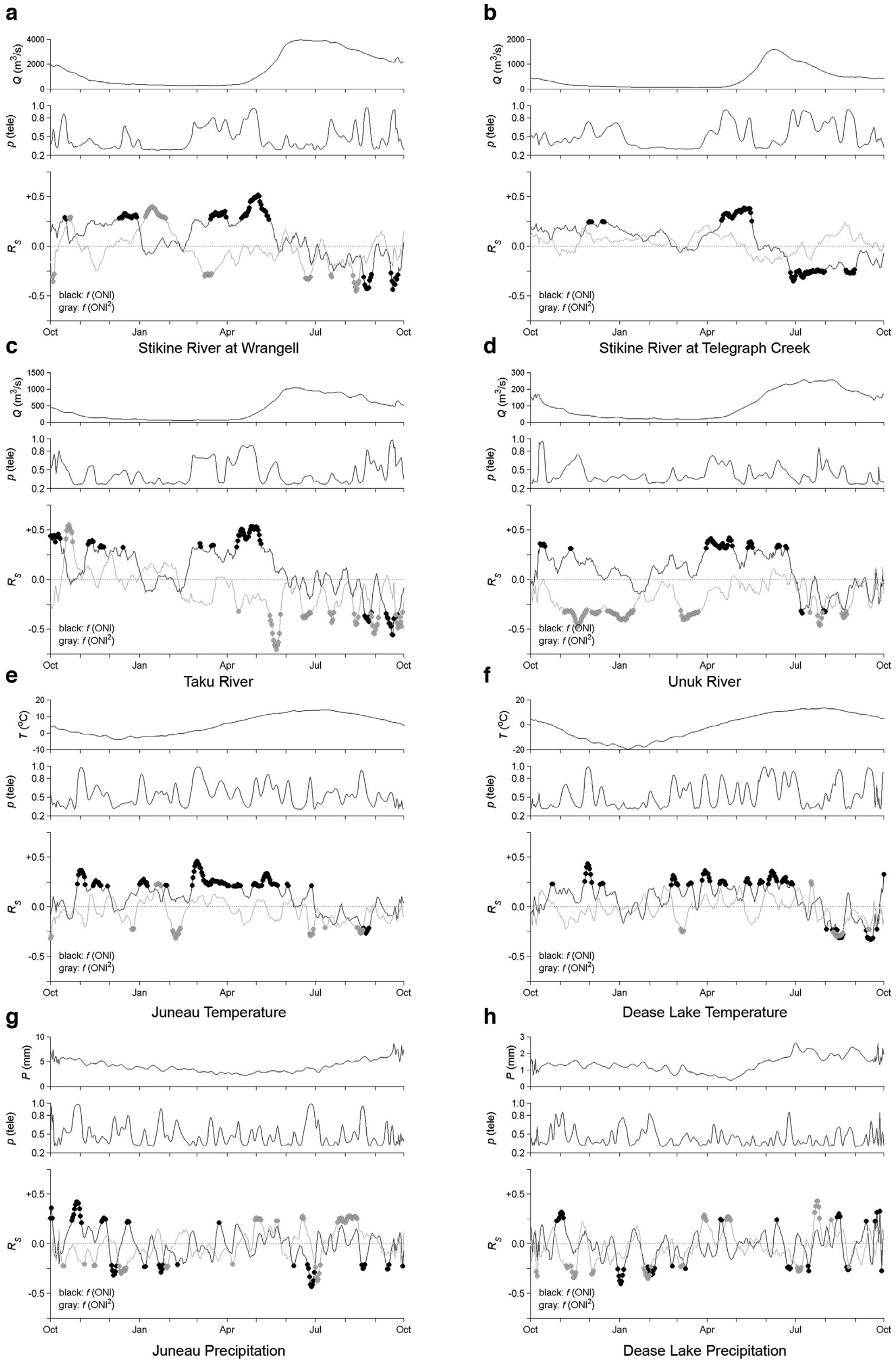

Fig. 3. ENSO results for four stream gages ((a)–(d)) and temperature and precipitation at two meteorological stations ((e)–(h)). The left column loosely corresponds to more coastal locations, whereas the right column corresponds to more inland locations. Each of the eight panels has three plots: the upper plot gives the mean annual regime; middle plot gives the probability that any teleconnection (linear or nonlinear) exists, as determined from AIC-based polynomial modeling; bottom plot gives Spearman correlation coefficients, with statistically significant relationships denoted by filled dots (see Table 2 for an interpretive key).

earlier onset of the melt freshet; the opposite effect predominates during La Niña years.

Second, a clear negative association between ONI and streamflow appears in mid-to-late summer, primarily in August but spanning approximately July through September depending again on the particular location (Fig. 3a–d). The correspondence of El Niño conditions to lower-than-average discharges for this time of year likely reflects the combined impact of several processes. One is the aforementioned earlier freshet due to warmer air temperatures the previous spring, and therefore earlier exhaustion of the seasonal snowpack and lesser opportunity for mid-to-late summer snowmelt runoff generation. That is, the normal seasonal recession to summer-autumn baseflow occurs earlier, giving lower-than-average late-summer flows. The other is a modest negative association between ONI and late-summer temperature (Fig. 3e and f). Glacial meltwater generation in western North America generally peaks around July through September following seasonal snowpack depletion. Thus, during El Niño years, cooler-than-normal late-summer air temperatures may reduce glacial melt runoff relative to neutral or cool-phase ENSO (La Niña) years.

In tandem, these two streamflow teleconnections – a positive association in springtime, and a negative association in mid-to-late summer – suggest that the signature of ENSO in these transboundary watersheds consists mainly of a temperature-driven seasonal timing shift. El Niño (La Niña) conditions lead to warmer (cooler) spring temperatures and an earlier (later) snowmelt freshet, moving some proportion of the annual water balance forward (backward) in the year. Interestingly, the intervening period between these two seasonal teleconnections, during which the annual flow maximum typically occurs as a result of peak seasonal snowmelt rates, possibly with superposed summer rainfall events, does not exhibit a clear ENSO teleconnection. It is unclear whether this null result simply reflects sampling variability, or instead some specific hydrometeorological mechanism, such as a dependence of summertime peak-flow conditions on erratic local-scale individual weather events or conditions regionally uncorrelated with ENSO.

Third, there is some evidence, which is somewhat weak and sporadic yet consistent across all four streamflow records, for a positive streamflow teleconnection to ONI following the start of the water year, around October–December (Fig. 3a–d). This anomaly occurs around the same time as modest positive associations between ONI and both temperature (Fig. 3e and f) and precipitation (Fig. 3g and h). The outcome suggests higher rainfall contributions to runoff in autumn and perhaps early winter during El Niño winters, due to both heavier precipitation and higher rain-to-snow ratios. That interpretation is consistent with the observation that the autumn–early winter streamflow teleconnection is weaker for the Stikine headwater basin (Fig. 3b) relative to the other locations (Fig. 3a, c, d). This WSC gage is located in the substantially colder and drier continental interior, where average temperatures drop below freezing by November (Fig. 3f), and autumn–early winter rainfall is generally a less important contributor to contemporaneous streamflow relative to the three other, more coastal basins.

Detailed interpretations were similarly performed for PDO, NPGO, and AO teleconnections. In the interest of brevity, only the most notable effects are summarized below; the full set of statistical outcomes can be found in Figs. 4–6. PDO responses (Fig. 4) are, broadly speaking, very similar to those for ENSO: positive streamflow associations at the start of the freshet, and negative streamflow associations in late summer, which appear to be generated primarily by a forward (backward) shift of the seasonal snowmelt freshet under increased (decreased) temperatures related to warm-phase (cold-phase) PDO conditions. In comparison to ENSO, the PDO temperature anomalies (Fig. 4e and f) are more seasonally long-lived, extending almost continuously from about October through May or even July, and also demonstrate some evidence for monotonic nonlinearity, although neither of these differences appears to be directly manifested in the corresponding streamflow teleconnections (Fig. 4a–d). There is also some statistical evidence for a parabolic (concave downward) PDO-streamflow association around the peak of the freshet in June. A similar, strongly nonlinear, teleconnection in temperature is apparent for Dease Lake, suggesting a potential temperature-driven mechanism for the parabolic melt-season streamflow teleconnection. However, the effect cannot be clearly seen in the Juneau temperature data, and its identification and interpretation must therefore remain tentative.

The NPGO outcomes (Fig. 5) are the most enigmatic of the four teleconnection patterns considered. Only one feature is uniformly apparent across all the hydrometric stations: a negative linear association during the onset and rising limb of the freshet, which is far stronger and more consistent for the Taku and coastal Stikine gages (Fig. 5a and c) than for the Unuk and inland Stikine gages (Fig. 5b and d), suggesting it may predominantly be a coastal feature. There is little evidence for a systematic precipitation teleconnection (Fig. 5g and h), and the temperature teleconnections appear to consist of a linear or perhaps monotonically nonlinear positive association during winter, followed by a possible parabolic (concave-upward) relationship in spring (Fig. 5e and f). These meteorological teleconnections offer little clear explanatory basis for the apparent streamflow teleconnection, which leads us to conservatively classify all the NPGO outcomes as a null result. That is, the statistical outcomes provide some intriguing preliminary indications of NPGO teleconnections, and the topic thus invites closer investigation, but at present we feel that our findings do not robustly reveal regionally coherent streamflow effects alongside associated meteorological driving mechanisms.

Finally, with respect to the AO, there is evidence for a temporally intermittent, but spatially consistent, monotonically nonlinear positive streamflow association in late spring through early fall (Fig. 6a–d). This discharge teleconnection is readily interpretable in terms of roughly contemporaneous, monotonically nonlinear, positive relationships between the AO index and both temperature (Fig. 6e and f) and precipitation (Fig. 6g and h). Thus, a positive AO state appears to be associated, albeit in a nonlinear fashion, with increases in both summer rainfall runoff and snow and glacier melt generation.

4. Discussion

To the extent that the outcomes from this study can be compared to prior literature for the region, the streamflow, temperature, and precipitation findings are broadly consistent with earlier teleconnection analyses (e.g., [4,20,61]). Many of the specific hydroclimatic processes inferred, such as higher autumn–winter streamflows or earlier snowmelt freshets under warmer air temperatures, have been widely observed either in this region, or alternatively in other areas of western North America (e.g., [3,22,25,68]). Our inference of higher-than-normal precipitation and streamflow in fall and early winter during ENSO and PDO warm phases is opposite to what is observed for the Pacific Northwest (PNW; [54,58]), to the south of our study area. This is consistent with a previously noted north-south see-saw in ENSO- and PDO-related precipitation variations along the northern Pacific coast of North America [20,77], which is analogous to another, perhaps better-known see-saw in ENSO precipitation teleconnections between the US PNW and the US Southwest (e.g., [69]). Also interesting are the results for the Arctic Oscillation, as the prior body of work on AO forcing of streamflow is far smaller than for ENSO and PDO, particularly in the BC-AK border region. To the extent the two studies can be compared given significant differences in methods and goals, our finding of higher temperature, precipitation, and streamflow during positive-phase AO years shows both similarities and differences with results for southwest Yukon Territory [21], a nearby but hydroclimatically distinct region to the northwest of our study area.

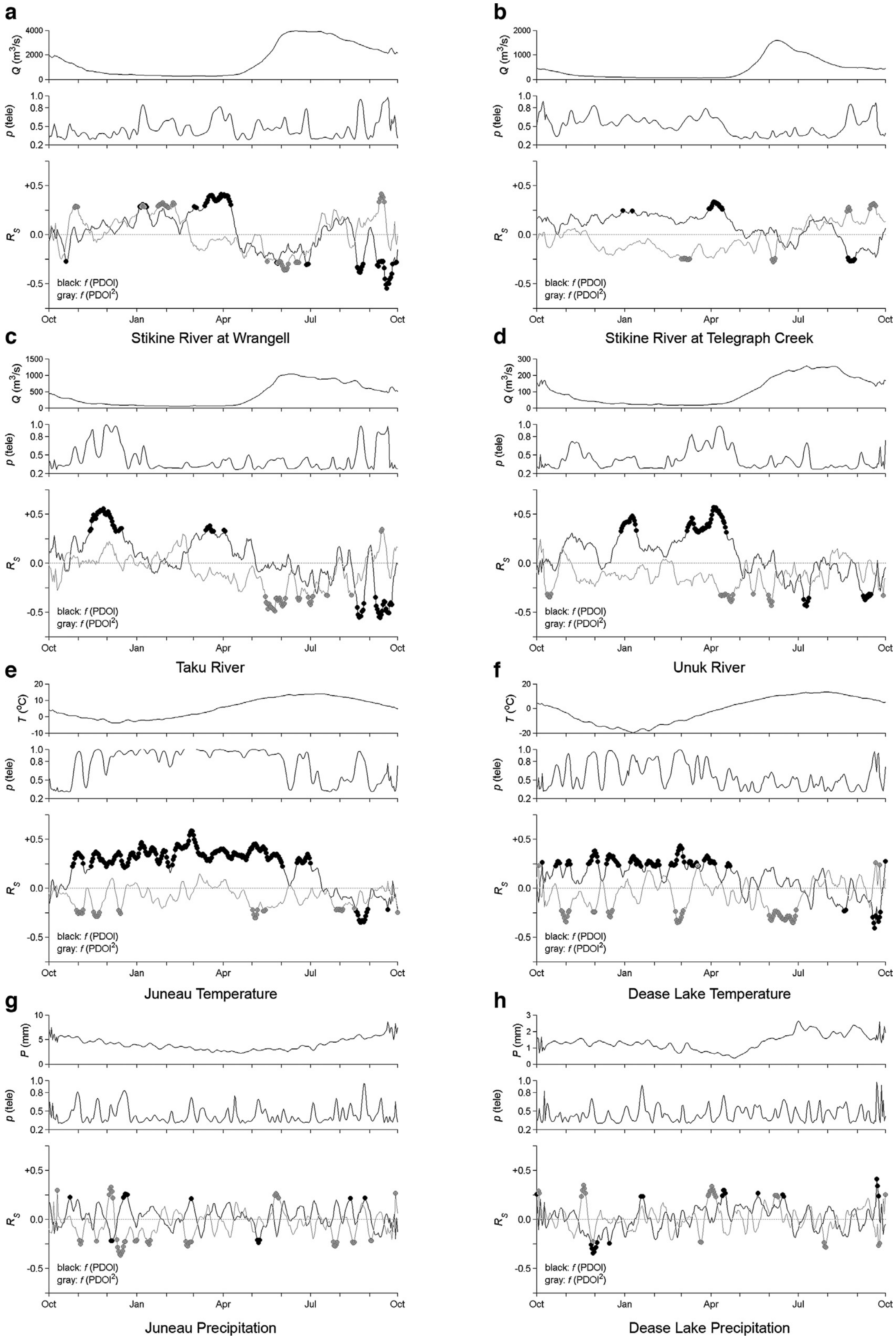

Fig. 4. As in Fig. 3, but for PDO.

A point of particular interest is the degree of nonlinearity in the observed responses. ENSO effects, for instance, exhibit some diversity. On the one hand, the spring temperature association appears linear, consistent with the neural network-based temperature analyses of Wu et al. [81] over southeast Alaska and northwest British Columbia. The corresponding springtime river discharge relationship to the ONI also appears predominantly linear, presumably reflecting relatively straightforward snowmelt rate responses. However, we also find that the subsequent, mid-to-late summer, streamflow teleconnection is monotonically nonlinear for most of the basins.

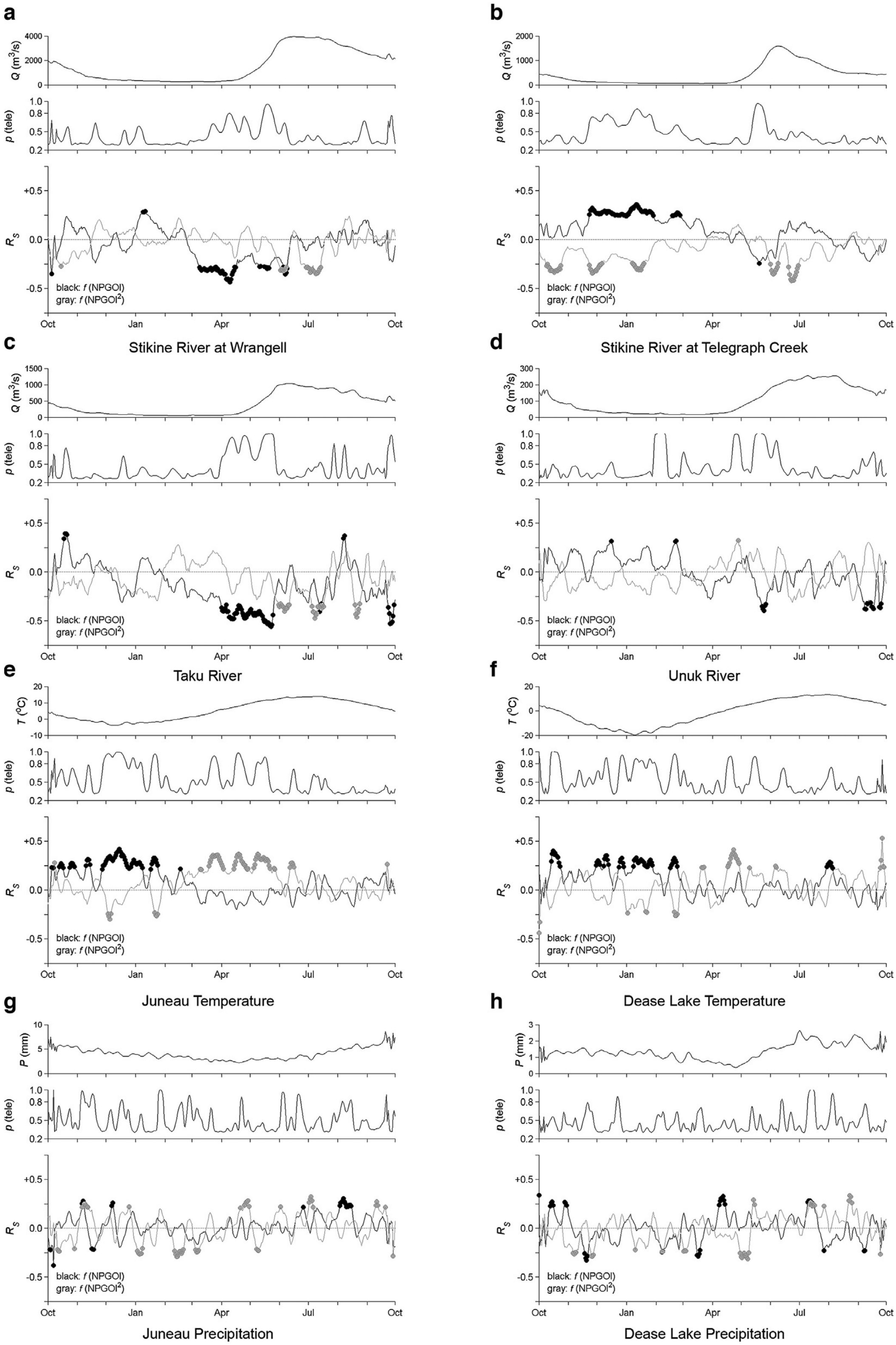

Fig. 5. As in Fig. 3, but for NPGO.

Recall that we attributed this mid-to-late summer ENSO-streamflow teleconnection to two distinct hydroclimatic processes. In turn, this suggests a minimum of two explanations, which are not mutually exclusive, for the monotonic nonlinearity of the teleconnection. The first explanation reflects an intersection between catchment characteristics and nonlinearity in the driving climatic teleconnection. The mid-to-late summer flow anomaly appears partially related to variations in glacier melt generation under a contemporaneous teleconnection in temperature, and this meteorological teleconnection is monotonically nonlinear. Such an interpretation is supported

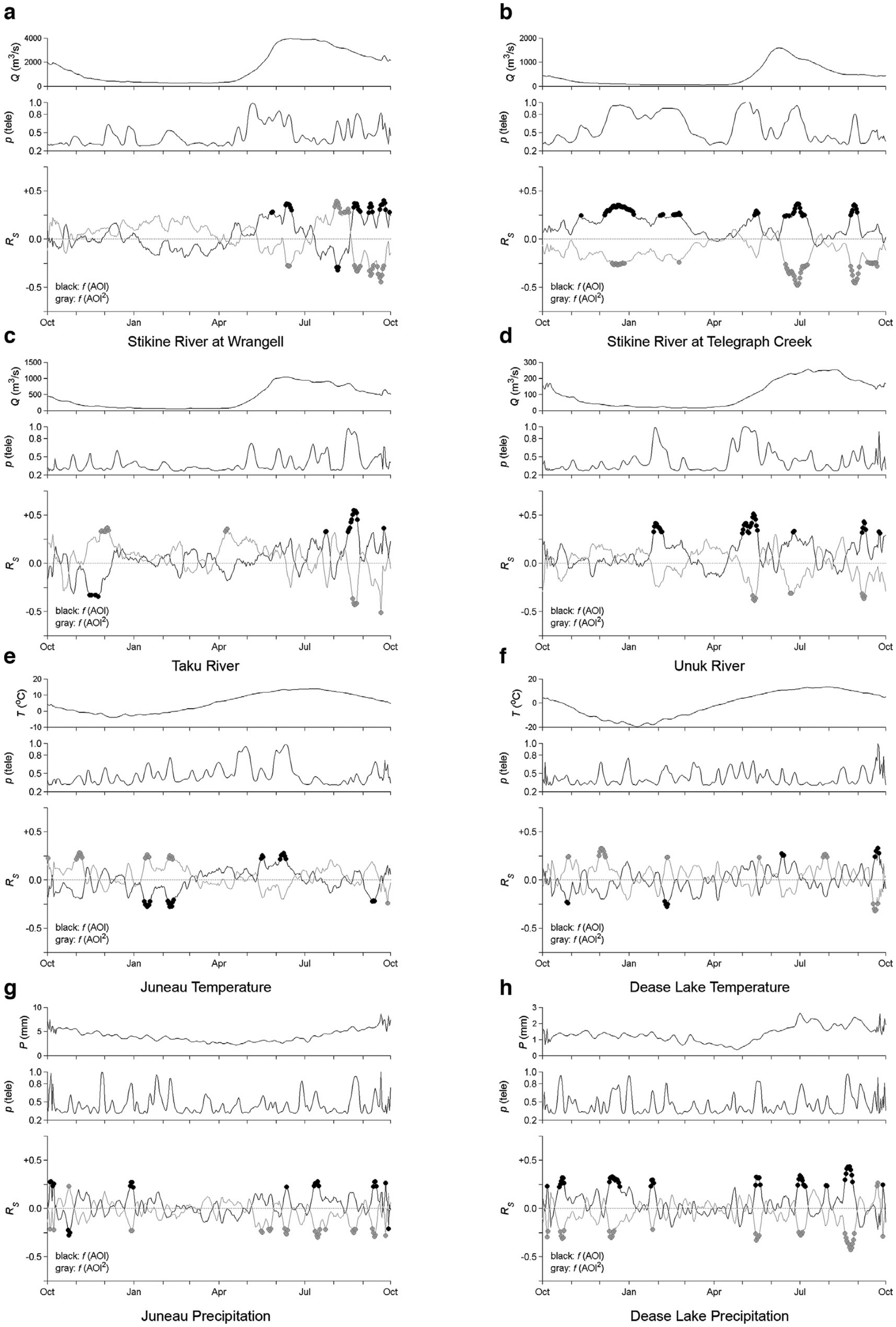

Fig. 6. As in Fig. 3, but for AO.

by the fact that the only hydrometric station for which this ONI-streamflow relationship is linear is the Stikine headwater basin at Telegraph Creek (cf. Fig. 3b vs. Fig. 3a, c, d), which is markedly less glacierized than the others (Table 1). The second explanation relates largely to terrestrial hydrologic processes. As noted above, the negative late-summer ENSO-flow association may additionally reflect earlier (later) exhaustion of the seasonal snowpack due to a warmer (cooler) preceding spring under El Niño (La Niña) conditions. River discharge recession to baseflow following the spring snowmelt peak reflects, in large part, catchment-scale water storage and release mechanisms – and broadly speaking, these processes can be profoundly nonlinear (e.g., [40,59]). Although the causal pathway whereby such nonlinearities might in turn specifically generate the nonlinear streamflow-climate relationship observed here is yet to be determined, there is abundant general precedent for fundamental modifications of streamflow teleconnections by various terrestrial hydrologic characteristics and processes (e.g., [9,22,32,61]). Note, however, that while both linear and monotonically nonlinear ENSO teleconnections are apparent, our analysis does not support strongly nonlinear (parabolic) ENSO teleconnections to meteorology or hydrology in this particular region.

More broadly, the streamflow and meteorological teleconnections contain a mixture of linear, monotonically nonlinear, and non-monotonically nonlinear relationships depending on the hydroclimatic variable, location, circulation pattern, and time of year. Monotonically nonlinear associations indicate that the water resource responses to the positive and negative phases of a given climate mode are not simple mirror images of each other. These have been widely observed for some ocean-atmosphere circulation patterns, including ENSO and PDO teleconnections in southeast Alaska and northwest BC (e.g., [20,25]). Generally speaking, strongly nonlinear (parabolic) streamflow teleconnections appear substantially less prevalent here than in some other areas of the northern hemisphere (cf. [18,19]). Compared to the meteorological analyses of Wu et al. [81], this outcome is loosely consistent for precipitation and strongly consistent for temperature, though they only considered the wintertime effects of ENSO.

Considering these outcomes alongside the large-scale water supply study of Fleming and Dahlke [18], we can also begin to resolve progressive shifts in the nonlinearity of hydrological responses to ENSO moving southward along the Pacific margin of North America. Starting with the northern part of the PCTR, there appear to be mainly linear and monotonically nonlinear responses in the BC-AK border region; moving southward into the PNW, the responses grow increasingly nonlinear; and fully parabolic relationships appear in northern California. South of the PCTR, in southern California, there appears to be a shift back to more linear ENSO effects.

In combination, the results confirm and extend the notion that while many of the hydroclimatic processes observed here are recognizable from studies in this or other areas of western North America, the BC-AK border is distinguished by a unique hydroclimatology distinct from that of neighboring regions. Mechanistically, the outcome appears to reflect the intersection of specific regional-scale meteorological teleconnections with particular terrestrial characteristics, such as extensive glacierization. This spatial heterogeneity has important implications for regionalization studies, for example. Given the limited hydrometric data availability for international BC-AK rivers, it also implies a need for increased hydrologic and climatic monitoring in this region going forward.

For climate modes and seasons demonstrating either monotonic or non-monotonic nonlinearity in this region – such as the teleconnections of streamflow to ENSO in mid-to-late summer, or to AO over much of the freshet – there are methodological ramifications. As water resource pressures mount, the requirement for accurate seasonal forecasting of water supply fluctuations will grow more intense [67]. This can be particularly important for international rivers, where institutions for transboundary water management benefit from and may specifically require operational forecasts; various water supply forecasting activities undertaken individually and collectively by both Canadian and US authorities for the transboundary Columbia River provide a nearby example. The most common and arguably still the most effective approach to seasonal-scale water supply forecasting in western North America remains statistical regressions upon various predictor variables, which increasingly include climate indices, such as those for ENSO or PDO (e.g., [25,38,67]). Conventionally, climate-water supply relationships are taken to be linear in such applications. However, simple steps can be taken to fully incorporate nonlinear teleconnections into this regression framework [18], and it is apparent that this may be necessary in some cases for the BC-AK border region.

Overall, the climate mode signatures are not strongly variable in space, but they are highly variable in time. On the one hand, the results show little systematic difference between hydrometric stations. Several studies have revealed the watershed regime-dependence of streamflow teleconnections, such as profound differences in the hydroclimatology of glacierized and non-glacierized basins (e.g., [12,22,61]). However, our present outcome is not surprising, as all three rivers have broadly similar flow regimes, dominated by spring-summer snow and ice melt. On the other hand, the main streamflow influences of ENSO, PDO, and AO are not evenly distributed across the year. Rather, most of these teleconnections occur over narrow seasonal windows corresponding specifically to autumn-fall rainfall runoff or the onset, the peak, or the falling limb of the seasonal snowmelt and/or glacier melt freshet. That is, across all of the ocean-atmospheric circulation patterns we examined in this region, the streamflow teleconnections are highly transient seasonal phenomena reflecting season-specific hydrological processes.

Such seasonally variant climate impacts may be relevant to any process or activity having a season-specific flow dependence. Given the strongly seasonal nature of many ecological processes, the attendant variations in fluvial aquatic habitat and delivery of freshwater and dissolved and suspended material to the coastal ocean may have particularly broad importance (e.g., [64,71]). Although an analysis of hydroecological linkages in this region is beyond the scope of this study, such linkages have been highlighted for marine and freshwater species at multiple tropic levels ([8,23,64]; see also [47]). These relationships are established by the transport and influence (variations in timing and magnitude) of freshwater runoff. In this ecosystem, water provides a strong bond between landscape change, habitat, streamflow and physical and chemical oceanographic conditions that support high primary productivity and a robust upper trophic level foodweb (e.g., [64,70]). The detailed mechanisms by which the various modes of interannual climate variability impact such relationships are an emergent topic of research (e.g. [46]). Implications of hydroclimatic forcing of the freshwater phase of the salmon life cycle for international BC-AK rivers are of special interest in the PCTR, particularly in light of joint Canada–US management of migratory salmon stocks under the 1985 Pacific Salmon Treaty, for instance. Assessing the implications of our hydrologic teleconnection analyses to salmon ecology in the BC-AK border region may therefore be a priority for future research.

Streamflow teleconnections may also interact in various ways with the hydrological impacts of longer-term climatic shifts, such as the ongoing amelioration of climate following the late 19th century end of the Little Ice Age or global-scale anthropogenic climate changes due to net atmospheric greenhouse gas emissions projected by the climate modeling community. Though fundamental changes in climate modes and teleconnections may occur, such changes have proven challenging to predict numerically (e.g., [44]). Also interesting, however, is the superposition of teleconnections upon anticipated long-term hydroclimatic regime changes. Under progressive warming, as rain-to-snow ratios rise, seasonal streamflow patterns in this region are likely to become increasingly characterized by an autumn-winter rainfall freshet and to exhibit a less pronounced spring-summer snowmelt freshet (e.g., [73]). Further, late-summer glacier melt contributions to flow will similarly change as glaciers continue to recede [43,64], which could initially take the form of an increased melt pulse but may eventually result in a flow decline (see also reviews by Jansson et al. [36] and Moore et al. [56]). As autumn-winter flows grow more prominent, their variations (such as the teleconnections to ENSO and PDO at this time of year) will grow commensurately more prominent as well. By the same token, as the snowmelt freshet as a whole becomes less pronounced over time, teleconnections involving spring-summer melt (such as various associations to ENSO, PDO, and AO over approximately March through July) may become a less notable feature of the overall hydroclimatic regime. Similarly, the prominence of the apparent glacier-mediated, temperature-related teleconnection to ENSO in late summer might be expected to first increase and then eventually decline, and in the limit of complete upstream ice mass loss ultimately disappear altogether, as glacier melt runoff first demonstrates a warming-generated pulse but then eventually declines and disappears. This late-summer streamflow teleconnection appears to be monotonically nonlinear, so it is conceivable that such changes in its overall prominence might be accompanied by a shift first toward greater teleconnection nonlinearity followed a shift toward more linear responses before, perhaps, disappearing altogether. Another interesting conclusion is that some aspects of the hydrological impacts of ENSO and PDO warm phases approximately mirror those that may be associated with possible longer-term climatic shifts. Thus, historically observed El Niño and PDO warm-phase conditions may serve as an analog for studying the potential impacts of other climatic effects in transboundary BC-AK rivers.

5. Conclusions

Several previously known features of the international border region between British Columbia, Canada and Alaska, USA draw attention to its hydroclimatology. These include the intrinsic management concerns for international rivers in general, and the ecosystem linkages provided by transboundary BC-AK rivers in particular, as they penetrate the Coast Mountains drainage divide between the coastal rainforest ecosystems of the northern PCTR and the cold, drier plateau of the continental interior. Additionally, these mountains are heavily glacierized, modifying river flows and lotic ecosystems. Runoff from the Alaskan coast, and in particular large international rivers like the Stikine, deliver massive freshwater fluxes and geochemical loads to the GOA, providing key controls on coastal ocean circulation and marine ecosystems. Landscapes here are shifting quickly under variations in climate and glacier recession. Studies of the hydroclimatology of the area in general, and of its border-spanning rivers in particular, have been valuable but sparse to date. To the extent that research has been conducted, it suggests deep complexities.

In response to this challenge, a collection of up-to-date time series analysis techniques was deployed to establish a fundamental framework for how several organized modes of climate variation affect the seasonal flows of transboundary BC-AK rivers. The methods avoid assumptions about statistical distributions and the nature of hydroclimatic nonlinearities; bring to bear both nonparametric null-hypothesis significance testing, and an information theoretic approach for model probability estimation; and focus on achieving high seasonal resolution. The analysis was performed using eight relatively long-term historical hydrometeorological datasets from six measurement locations. Although station coverage in this remote frontier region is thin, streamgage data are spatially integrated measurements of upstream catchment processes, and in this sense a substantial portion of the BC-AK border region is directly sampled here, including its largest river.

The outcomes refine and expand existing understanding of the region's water resource responses to climatic variability. The leading hydrological effect of large-scale ocean-atmosphere circulation patterns here is to influence seasonal flow timing through temperature-driven melt rate variations. This is most clearly seen for ENSO and PDO, which affect river regimes in the region by shifting snowmelt forward or backward in time, expressed as changes in the magnitudes of the rising and falling limbs of the spring-summer freshet. A number of intriguing secondary effects are additionally observed. A glacier-specific pathway for ENSO teleconnectivity to river discharge was identified, adding to the growing literature on modulation of hydroclimatic dynamics by mountain glaciers. These icemelt-mediated runoff variations reinforce the late-summer flow decrease (increase) under El Niño (La Niña) conditions mentioned above. Warm-phase ENSO or PDO conditions also appear associated with a modest flow increase in autumn through early winter, interpreted to reflect higher rain-to-snow ratios and a slight precipitation increase. No clear NPGO signature in seasonal streamflow can be claimed on the basis of these analyses, although it cannot be conclusively ruled out. The AO, however, has interesting impacts. While most of the teleconnections were primarily related to temperature in this area, positive-phase AO conditions appear to generate increases in both temperature and precipitation over mid- to late-summer, yielding increased flows through much of the freshet. Finally, the parabolic teleconnections observed for several locations globally, and perhaps most notably in the southern PCTR of northern California, are not widely seen here; however, there is evidence for monotonically nonlinear ENSO, PDO, and AO effects in both surface climate and streamflow. In combination with prior work, these outcomes allow us to begin confidently tracing out patterns in the nonlinearity of water resources responses to ENSO along the entire Pacific margin of North America. The results have implications for international water resource management, freshwater and coastal ecology studies, and assessments of possible longer-term climate and glacier change impacts in the British Columbia-Alaska border region.

Acknowledgments

The streamflow data used in this study are available online from the US Geological Survey (USGS) at waterdata.usgs.gov/nwis/sw and Water Survey of Canada (WSC) at www.ec.gc.ca/rhc-wsc. Meteorological time series data are publicly available from the US National Oceanographic and Atmospheric Administration (NOAA) at www.ncdc.noaa.gov/cdo-web and Meteorological Service of Canada (MSC) at www.ec.gc.ca/dccha-ahccd. We thank Ed Neal and two anonymous reviewers for their helpful comments on an earlier draft of this manuscript. E.H. and S.O. were supported by the Alaska Climate Science Center. Parts of this work were produced by Crown authors and authors of the U.S. government.

References

[1] Arendt A, Bliss A, Bolch T, Cogley JG, Gardner AS, Hagen J-O, et al. Randolph Glacier Inventory – A Dataset of Global Glacier Outlines: Version 4.0, Global Land Ice Measurements from Space. Boulder Colorado, USA: Digital Media; 2014.

[2] Bai X, Wang J, Sellinger C, Clites A, Assel R. Interannual variability of Great Lakes ice cover and its relationship to NAO and ENSO. J Geophys Res 2012;117. http://dx.doi.org/10.1029/2010JC006932.

[3] Beebee RA, Manga M. Variation in the relationship between snowmelt runoff in Oregon and ENSO and PDO. J Am Water Resour Assoc 2004;40:1011–24. http://dx.doi.org/10.1111/j.1752-1688.2004.tb01063.x.

[4] Bieniek PA, Walsh JE, Thoman RL, Bhatt US. Using climate divisions to analyze variations and trends in Alaska temperature and precipitation. J Clim 2014;27:2800–18. http://dx.doi.org/10.1175/JCLI-D-13-00342.1.

[5] Bitz CM, Battisti DS. Interannual to decadal variability in climate and glacier mass balance in Washington, western Canada, and Alaska. J Clim 1999;12:3181–96. http://dx.doi.org/10.1175/1520-0442(1999)012⟨3181:ITDVIC⟩2.0.CO;2.

[6] Böhmelt T, Bernauer T, Buhaug H, Gleditsch NP, Tribaldos T, Wischnath G. Demand, supply, and restraint: determinants of domestic water conflict and cooperation. Global Environ Change 2014;29:337–48. http://dx.doi.org/10.1016/j.gloevncha.2013.11.018.

[7] Bond NA, Overland JE, Spillane M, Stabeno P. Recent shifts in the state of the North Pacific. J Geophys Res 2003;30. http://dx.doi.org/10.1029/2003GL018597.

[8] Bryant M. Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of southeast Alaska. Clim Change 2009;95:169–93. http://dx.doi.org/10.1007/s10584-008-9530-x.

[9] Chen J, Kumar P. Role of terrestrial hydrologic memory in modulating ENSO impacts in North America. J Clim 2002;15:3569–85. http://dx.doi.org/10.1175/1520-0442(2003)015⟨3569:ROTHMI⟩2.0.CO;2.

[10] Clarke GKC, Jarosch AH, Anslow FS, Radić V, Menounos B. Projected deglaciation of western Canada in the twenty-first century. Nat Geosci 2015;8:372–7. http://dx.doi.org/10.1038/ngeo240.

[11] Cook BI, Seager R, Miller RL. On the causes and dynamics of the early twentieth-century North American pluvial. J Clim 2011;24:5043–60. http://dx.doi.org/10.1175/2011JCLI4201.1.

[12] Dahlke HE, Lyon SW, Stedinger JR, Rosqvist G, Jansson P. Contrasting trends in hydrologic extremes for two sub-arctic catchments in northern Sweden: does glacier melt matter? Hydrol Earth Syst Sci 2012;16:2123–41. http://dx.doi.org/10.5194/hess-16-2123-2012.

[13] Déry SJ, Stahl K, Moore RD, Whitfield PH, Menounos B, Burford JE. Detection of runoff timing changes in pluvial, nival, and glacial rivers of western Canada. Water Resour Res 2009;45. http://dx.doi.org/10.1029/2008WR006975.

[14] Dettinger MD, Ralph FM, Das T, Neiman PJ, Cayan DR. Atmospheric rivers, floods and the water resources of California. Water 2011;3:445–78. http://dx.doi.org/10.3390/w302044.

[15] Di Lorenzo E, Schneider N, Cobb KM, Franks PJS, Chhak K, Miller AJ, et al. North Pacific Gyre Oscillation links ocean climate and ecosystem change. Geophys Res Lett 2008;35. http://dx.doi.org/10.1029/2007GL032838.

[16] Dracup JA, Kayha E. The relationships between U.S. streamflow and La Niña events. Water Resour Res 1994;30:2133–41. http://dx.doi.org/10.1029/94WR00751.

[17] Fleming SW, Barton M. Climate trends but little net water supply shift in one of Canada's most water-stressed regions over the last century. J Am Water Resour Assoc 2015;51:833–41. http://dx.doi.org/10.1111/jawr.12281.

[18] Fleming SW, Dahlke HE. Parabolic northern-hemisphere river flow teleconnections to El Niño-Southern Oscillation and the Arctic Oscillation. Environ Res Lett 2014;8. http://dx.doi.org/10.1088/1748-9326/9/10/104007.

[19] Fleming SW, Dahlke HE. Modulation of linear and nonlinear hydroclimatic dynamics by mountain glaciers in Canada and Norway: results from information-theoretic polynomial selection. Can Water Resour J/Revue canadienne des ressources hydriques 2014;39:324–41 (see also Erratum). http://dx.doi.org/10.1080/07011784.2014.942164.

[20] Fleming SW, Whitfield PH. Spatiotemporal mapping of ENSO and PDO surface meteorological signals in British Columbia, Yukon, and southeast Alaska. Atmos Ocean 2010;48:122–31. http://dx.doi.org/10.3137/AO1107.2010.

[21] Fleming SW, Moore RD, Clarke GKC. Glacier-mediated streamflow teleconnections to the Arctic Oscillation. Int J Climatol 2006;26:619–36. http://dx.doi.org/10.1002/joc.1273.

[22] Fleming SW, Whitfield PH, Moore RD, Quilty EJ. Regime-dependent streamflow sensitivities to Pacific climate modes across the Georgia-Puget transboundary ecoregion. Hydrol Processes 2007;21:3264–87. http://dx.doi.org/10.1002/hyp.6544.

[23] Gargett AE. The optimal stability 'window': a mechanism underlying decadal fluctuations in North Pacific salmon stocks? Fish Oceanogr 1997;6:109–17. http://dx.doi.org/10.1046/j.1365-2419.1997.00033.x.

[24] Gershunov A, Barnett TP. Interdecadal modulation of ENSO teleconnections. Bull Am Meteorol Soc 1998;79:2715–25 http://dx.doi.org/10.1175/1520-0477(1998)079 .

[25] Gobena AK, Weber FA, Fleming SW. The role of large-scale climate modes in regional streamflow variability and implications for water supply forecasting: a case study of the Canadian Columbia River Basin. Atmos Ocean 2013;51:380–91. http://dx.doi.org/10.1080/07055900.2012.759899.

[26] Hague MJ, Ferrari MR, Miller JR, Patterson DA, Russell GL, Farrell AP, et al. Modelling the future hydroclimatology of the lower Fraser River and its impacts on the spawning migration survival of sockeye salmon. Global Change Biol. 2011;17:87–98. http://dx.doi.org/10.1111/j.1365-2486.2010.02225.

[27] Hamlet AF, Huppert D, Lettenmaier DP. Economic value of long-lead streamflow forecasts for Columbia River hydropower. J Water Res Pl-ASCE 2002;128:91–101. http://dx.doi.org/10.1061/(ASCE)0733-9496(2002)128:2(91).

[28] Hammond JC. Trends in streamflow above and below dams across the Columbia River Basin from 1950 to 2012: assessing sub-basin sensitivity (M.S. thesis). Corvallis: Oregon State University; 2014.

[29] Hatcher KA, Jones JA. Climate and streamflow trends in the Columbia River Basin: evidence for ecological and engineering resilience to climate change. Atmos Ocean 2013;51:436–55. http://dx.doi.org/10.1080/07055900.2013.808167.

[30] Helsel DR, Hirsch RM. Statistical methods in water resources. Reston, VA: US Geological Survey; 2002.

[31] Hill DF, Bruhis N, Calos SE, Arendt A, Beamer J. Spatial and temporal variability of freshwater discharge into the Gulf of Alaska. J Geophys Res Oceans 2015;120:634–46. http://dx.doi.org/10.1002/2014JC010395.

[32] Hodgkins GA. Streamflow changes in Alaska between the cool phase (1947-1976) and the warm phase (1977-2006) of the Pacific Decadal Oscillation: the influence of glaciers. Water Resour Res 2009;45. http://dx.doi.org/10.1029/2008WR007575.

[33] Hoerling MP, Kumar A, Zhong M. El Niño, La Niña, and the nonlinearity of their teleconnections. J Clim 1997;10:1769–86. http://dx.doi.org/10.1175/1520-0442(1997)010⟨1769:ENOLNA⟩2.0.CO;2.

[34] Hsieh WW. Machine learning methods in the environmental sciences. Cambridge, UK: Cambridge University Press; 2009. p. 364.

[35] Hsieh WW, Wu A, Shabbar A. Nonlinear atmospheric teleconnections. Geophys Res Lett 2006;33. http://dx.doi.org/10.1029/2005GL025471.

[36] Jansson P, Hock R, Schneider T. The concept of glacier storage: a review. J Hydrol 2003;282:116–29. http://dx.doi.org/10.1016/S0022-1694(03)00258-0.

[37] Kellogg E. Coastal temperate rain forests: ecological characteristics, status and distribution worldwide. Portland: Ecotrust and Conservation International; 1992.

[38] Kennedy AM, Garen DC, Koch RW. The association between climate teleconnection indices and Upper Klamath seasonal streamflow: trans-Niño index. Hydrol Processes 2009;23:973–84. http://dx.doi.org/10.1002/hyp.7200.

[39] Khan S, Ganguly AR, Bandyopadhyay S, Saigal S, Erickson III DJ, Protopopescu V, et al. Nonlinear statistics reveals stronger ties between ENSO and the tropical hydrological cycle. Geophys Res Lett 2006;33:L24402. http://dx.doi.org/10.1029/2006GL027941.

[40] Kirchner JW. Catchments as simple dynamical systems: catchment characterization, rainfall-runoff modeling, and doing hydrology backward. Water Resour Res 2009;45. http://dx.doi.org/10.1029/2008WR006912.

[41] Kousky VE, Higgins RW. An alert classification system for monitoring and assessing the ENSO cycle. Weather Forecasting 2007;22:353–71. http://dx.doi.org/10.1175/WAF987.1.

[42] Larsen CF, Motyka RJ, Arendt AA, Echelmeyer KA, Geissler PE. Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise. J Geophys Res 2007;112. http://dx.doi.org/10.1029/2006JF00058.

[43] Larsen CF, Burgess E, Arendt AA, O'Neel S, Johnson AJ, Kienholz C. Surface melt dominates Alaska glacier mass balance. Geophys Res Lett 2015. http://dx.doi.org/10.1002/2015GL064349.

[44] Latif M, Keenlyside NS. El Niño/Southern Oscillation response to global warming. Proc Natl Acad Sci USA 2009;106:20578–83. http://dx.doi.org/10.1073/pnas.0710860105.

[45] Leopold LB. A view of the river. Cambridge: Harvard University Press; 1994.

[46] Litzow MA, Mueter FJ. Assessing the ecological importance of climate regime shifts: an approach from the North Pacific Ocean. Prog Oceanogr 2014;120:110–19. http://dx.doi.org/10.1016/j.pocean.2013.08.003.

[47] Lydersen C, Assmy P, Falk-Petersen S, Kohler J, Kovacs KM, Reigstad M, et al. The importance of tidewater glaciers for marine mammals and seabirds in Svalbard, Norway. J Mar Syst 2014;129:452–71. http://dx.doi.org/10.1016/j.jmarsys.2013.09.006.

[48] Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull Am Meteorol Soc 1997;78:1069–79. http://dx.doi.org/10.1175/1520-0477(1997)078⟨1069:APICOW⟩2.0.CO;2.

[49] Mao Y, Nijssen B, Lettenmaier DP. Is climate change implicated in the 2013-2014 California drought? A hydrologic perspective. Geophys Res Lett 2015;42:2805–13. http://dx.doi.org/10.1002/2015GL063456.

[50] McCabe GJ, Dettinger MD. Primary modes and predictability of year-to-year snowpack variations in the Western United States from teleconnections with Pacific Ocean Climate. J Hydrometeorol 2002;3:13–25 http://dx.doi.org/10.1175/1525-7541(2002)003 .

[51] Mekis É, Vincent LA. An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada. Atmos Ocean 2011;49:163–77. http://dx.doi.org/10.1080/07055900.2011.583910.

[52] Meko DM, Stockton CW, Boggess WR. The tree-ring record of severe sustained drought. J Am Water Resour Assoc 1995;31:789–801. http://dx.doi.org/10.1111/j.1752-1688.1995.tb03401.x.

[53] Micovic Z, Quick MC. Investigation of the model complexity required in runoff simulation at different time scales. Hydrol Sci J 2009;54:872–85. http://dx.doi.org/10.1623/hysj.54.5.872.

[54] Miles EL, Snover AK, Hamlet AF, Callahan B, Fluharty D. Pacific Northwest regional assessment: the impacts of climate variability and climate change on the water resources of the Columbia River Basin. J Am Water Res Assoc 2000;36:399–420. http://dx.doi.org/10.1111/j.1752-1688.2000.tb04277.x.

[55] Mitchell JM Jr, Dzerdzeevskii B, Flohn H, Hofmeyr WL, Lamb HH, Rao KN, et al. Climatic change. Technical Note 79, Geneva: World Meteorological Organization; 1966. p. 79.

[56] Moore RD, Fleming SW, Menounos B, Wheate R, Fountain A, Stahl K, et al. Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. Hydrol Processes 2009;23:42–61. http://dx.doi.org/10.1002/hyp.7162.

[57] Morrison J, Foreman MGG, Masson D. A method for estimating monthly freshwater discharge affecting British Columbia Coastal waters. Atmos Ocean 2012;50:1–8. http://dx.doi.org/10.1080/07055900.2011.63766.

[58] Mote PW, Parson EA, Hamlet AF, Keeton WS, Lettenmaier D, Mantua N, et al. Preparing for climatic change: the water, salmon and forests of the Pacific Northwest. Clim Change 2003;61:45–88.

[59] Mudelsee M. Long memory of rivers from spatial aggregation. Water Resour Res 2007;43. http://dx.doi.org/10.1029/2006WR005721.

[60] Neal EG, Hood E, Smikrud K. Contribution of glacier runoff to freshwater discharge into the Gulf of Alaska. Geophys Res Lett 2010;37:L06404. http://dx.doi.org/10.1029/2010GL042385.

[61] Neal EG, Walter MT, Coffeen C. Linking the pacific decadal oscillation to seasonal stream discharge patterns in Southeast Alaska. J Hydrol 2002;263:188–97. http://dx.doi.org/10.1016/S0022-1694(02)00058-6.

[62] Newman M. Interannual to decadal predictability of tropical and north Pacific sea surface temperatures. J Clim 2007;20:2333–56.

[63] O'Neel S, Hood E, Arendt AA, Sass L. Assessing streamflow sensitivity to variations in glacier mass balance. Clim Change 2014. http://dx.doi.org/10.1007/s10584-013-1042-7.

[64] O'Neel S, Hood E, Bidlack AL, Fleming S, Arimitsu ML, Arendt AA, et al. Icefield-to-ocean linkages across the northern Pacific coastal temperate rainforest ecosystem. Bioscience 2015;65:499–512. http://dx.doi.org/10.1093/biosci/biv027.

[65] Pagano T, Garen D. A recent increase in western U.S. streamflow variability and persistence. J Hydrometeorol 2005;6:173–9. http://dx.doi.org/10.1175/JHM410.1.

[66] Penland C. A stochastic model of IndoPacific sea surface temperature anomalies. Physica D 1996;98:534–58. http://dx.doi.org/10.1016/0167-2789(96)00124-8.

[67] Perkins TR, Pagano TC, Garen DC. Innovative operational seasonal water supply forecasting technologies. J Soil Water Conserv 2009;64:15–17. http://dx.doi.org/10.2489/jswc.64.1.15A.

[68] Regonda SK, Rajagopalan B, Clark M, Pitlick J. Seasonal cycle shifts in hydroclimatology over the Western United States. J Clim 2005;18:372–84. http://dx.doi.org/10.1175/JCLI-3272.1.

[69] Redmond KT, Koch RW. Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. Water Resour Res 1991;27:2381–99. http://dx.doi.org/10.1029/91WR00690.

[70] Renner M, Arimitsu ML, Piatt JF. Structure of marine predator and prey communities along environmental gradients in a glaciated fjord. Can J Fish Aquat Sci 2012;69:2029–45. http://dx.doi.org/10.1139/f2012-117.

[71] Riche O, Johannessen SC, Macdonald RW. Why timing matters in a coastal sea: trends, variability, and tipping points in the Straight of Georgia, Canada. J Mar Syst 2014;131:36–53. http://dx.doi.org/10.1016/j.jmarsys.2013.11.003.

[72] Royer TC. Baroclinic transport in the Gulf of Alaska. Part II. Fresh water driven Alaska Coastal Current. J Mar Res 1981;39:251–66.

[73] Shanley CS, Pyare S, Goldstein MI, Alaback PB, Albert DM, Beier CM, et al. Climate change implications in the northern coastal temperate rainforest of North America. Clim Change 2015;130:155–70. http://dx.doi.org/10.1007/s10584-015-1355-9.

[74] Stockton CW, Jacoby GC Jr. Long-term surface-water supply and streamflow trends in the Upper Colorado River Basin, Lake Powell Research Project. Bulletin No. 18, Los Angeles, California: Institute of Geophysics and Planetary Physics, University of California; 1976.

[75] Vincent LA, Wang XL, Milewska EJ, Wan H, Yang F, Swail V. A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis. J Geophys Res 2012;117(D18). http://dx.doi.org/10.1029/2012JD017859.

[76] Wallace JM, Thompson DWJ. Annular modes and climate prediction. Phys Today 2002;55:28–33. http://dx.doi.org/10.1063/1.1461325.

[77] Walters RA, Meier MF. Variability in glacier mass balances in western North America. In: Peterson DH, editor. Aspects of climate variability in the Pacific and the Western Americas, Geophysical Monograph 55. American Geophysical Union; 1989. p. 365–74.

[78] Whitfield PH, Cannon AJ, Reynolds CJ. Modelling streamflow in present and future climates: examples from the Georgia Basin, British Columbia. Can Water Resour J/Revue canadienne des ressources hydriques 2002;27:427–56. http://dx.doi.org/10.4296/cwrj2704427.

[79] Whitfield PH, Spence C. Estimates of Canadian Pacific Coast runoff from observed streamflow data. J Hydrol 2011;410:141–9. http://dx.doi.org/10.1016/j.jhydrol.2011.05.057.

[80] Wolf AT. Conflict and cooperation along international waterways. Water Policy 1998;1:251–65. http://dx.doi.org/10.1007/978-94-011-4219-9_18.

[81] Wu A, Hsieh WW, Shabbar A. The nonlinear patterns of North American winter temperature and precipitation associated with ENSO. J Clim 2005;18:1736–52. http://dx.doi.org/10.1175/JCLI3372.1.