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

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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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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,