Chapter 26: Cold Region Hydrologic Models and Applications

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Abstract

Over the recent decades, the warming in Arctic has affected changes in the terrestrial hydrologic processes. Unfortunately, the number of hydro-meteorological observing stations in the region has decreased. To reduce the limitation in observation, a number of process-based and distributed models have been developed for simulating the hydrological processes in a changing climate. The current generations of models are able to reasonably reproduce the prominent cold region hydrologic processes, such as degrading permafrost, decreasing snow extent, increasing river discharge and evapotranspiration, and increasing streamflow temperature. These models enhance our understanding of the response of Arctic terrestrial processes to climate change and variation. However, the model representations for some of the Arctic hydrological processes are still not yet sufficient and need further improvements. This chapter provides an overview of changes in key processes and conditions of the Arctic terrestrial hydrology based on a synthesis of observations and model simulations, and presents recommendations for further development and improvement of cold region hydrologic models.

1. Introduction

The Arctic system is composed of various components and processes that are complexly intertwined through interaction and feedback. A change in one of the system components influences the others, hence further amplifying the magnitude of the change through those complex implication. The Arctic is currently undergoing changes never before seen in historic times, such as decreasing sea ice, degrading permafrost, decreasing snow cover, and expanding lake and wetland. These changes are closely connected to the hydrological cycle and the freshwater budget of the Arctic region. The Arctic terrestrial regions are covered by cryospheric components (e.g., glacier and snow) that are very vulnerable to climate warming and the freshwater from this region has the potential to disrupt deep convection of the Arctic Ocean, although the annual amounts are smaller (Prowse et al., 2015). Both observations and simulations have addressed the changes in the Arctic freshwater system, particularly permafrost degradation and increases in river discharge (Peterson et al., 2002). The increase in river discharge was very significant in the recent few decades when the Arctic warming was intensive. These changes have the potential to strongly influence the freshwater and heat budget of the Arctic Ocean and thus the global ocean circulation (Jahn and Holland, 2013), sea level rise (Rignot et al., 2011), and the terrestrial carbon cycle (Wrona et al., 2016).

The changes in the Arctic system have been captured through observations. Russia has a long history of hydrological observations in its territory starting from the beginning of the twentieth century. The observations are mostly made at the tributaries as well as the outlet of large rivers, and those measurements have provided evidence showing the increasing discharge from the Russian large rivers (Peterson et al., 2002). However, the number of observational stations began to decrease with the collapse of the old Soviet Union, and the data quality has simultaneously suffered due to the decreasing number of observational experts. In North America, there is a gradual move towards replacing most manual measurements to automatic systems, while the station density is continuously decreasing. In particular, the decrease in northern Canada is worrisome, especially since the end of 1970s (Park et al., 2015). The reduction in the number of measuring stations affect the quality of assessments of the environmental changes. Satellite observations may supplement the reduced number of measuring stations; however, they still have technical limitations in Arctic monitoring, sometimes even increasing uncertainties in the observational records. Hence, it still remains challenging to quantitatively estimate the freshwater budget of the Arctic region from the satellite observations, and their shorter and more recent observational periods limit the extrapolation of the observations to different time periods and regions.

A large proportion of runoff from the Arctic terrestrial drainage system (up to 41% according to WCRP, 1996) originates from ungagged basins and even those that are gaged are based on scattered measurement over large regions and for relatively short time periods. Therefore, models are essential as a means of extrapolating from those available measurements in both space and time, particularly to the ungagged catchments (where measurements are not available) and into the future (where measurements are not possible) to assess the likely impacts of future hydrological change (Beven, 2012). Cold region hydrological models can helps us to achieve a consistent and representative estimate of the magnitude and spatial distribution of the ever changing Arctic terrestrial water budget for both the contemporary and future time periods. Such models are also an integral and necessary part of the scientific investigation process and provide a powerful tool for developing and testing hypotheses with respect to various hydrologic processes (Lique et al. 2017).

Land surface hydrologic variables were regarded as separable parameters that could be independently prescribed as boundary conditions within climate models. Hence, land surface models (LSMs) were developed to simulate energy, water, and carbon exchanges between the atmosphere and the terrestrial surface over a wide range of time and space scales based on empirical and physical principles. The model simulations helped our understanding for changes of the terrestrial processes in regions with different landscapes and climates. LSMs have been incorporated into climate models (e.g., general circulation models and regional climate models) as the lower boundary of those models. Manabe (1969) developed the first generation of LSM, a bucket model with constant soil depth and water-holding capacity. The model expressed that evaporation is controlled by soil water content and precipitation generates runoff as soil moisture exceeds the saturation level. In 1980s, the radiative, momentum, and heat/mass transfer properties of vegetation surface were parameterized into LSM, including more biophysical control of the vegetation–soil system to evapotranspiration (Dicknson, 1984; Sellers et al., 1986). Canadian LSM emphasized the importance of boreal winter processes in the simulation of global climate (Verseghy et al., 1993). LSMs have also treated the surface vegetation as one of the prescribed parameters. During the past few decades, however, various dynamic global vegetation models have been developed and coupled into the land surface model, which made it possible to simulate vegetation change and the associated hydrological and biogeochemical fluxes in responses to climate warming (Foley et al., 1996; Cox et al., 1998; Levis et al., 2004).

However, the description of hydrological processes quite widely varies between LSMs. Hydrologic models are generally simplifications of the real system, and they can be of different levels of complexity and may incorporate different component interactions (Lique et al., 2016). For example, *empirical models* can be built by identifying empirical relationships amongst different hydrologic process variables based on field observations or laboratory measurements, while *conceptual models* can be designed to illustrate how the different processes across the hydrologic system link together and interact with each other. The relationships in conceptual model may be more or less complex, but usually employs simple mass balance equations. On the other hand, processed-based hydrological models integrate mathematical relationships describing the dominant fluxes of energy and water in each of the various space and time dependent hydrological processes, such as snow cover evolution, permafrost dynamic, infiltration, etc. While *distributed models* try to solve these mathematical relationships over a uniformly distributed grid with the aim of representing spatial variability and hydrologic connectivity throughout the model domain, *semi-distributed models* lump the various physical processes and their parameters in to sub-basins so that they are easier to setup and require relatively shorter running time.

Typical futures of cold-region hydrologic models are that they use physically-based algorithms to quantify hydrological cycle and cold-region hydrological processes, such as blowing snow, snow interception in forest canopies, sublimation, snowmelt, infiltration into frozen soils, permafrost-dynamics, actual evaporation, and radiation exchange to complex surfaces (Pomeroy et al., 2007). These processes are strongly intertwined and the effects of any disturbed processes are generally revealed within shorter time scale, while some has longer memory that the effects appear on seasonal and/or annual scales. One particular example is permafrost, where changes to some disturbances may last from over a season to a century scale, strongly affecting the Arctic hydrology. Many LSMs still have some specific problems, such as, too shallow soil columns representing the permafrost dynamics (Koven et al., 2013; Slater and Lawrence, 2013). However, the models have improved some important dynamical processes such as perched or suprapermafrost water table (Swenson et al., 2012), excess ice (Lee et al., 2014), and hydrological impact of organic soils (Lawrence and Slater, 2008). Snow processes are strongly implicated in the permafrost thermal state as well as river discharge. Most LSMs represent the snow processes based on physical principles, which soundly capture earlier snowmelt induced by the warming climates and hence earlier timing of spring peak discharge (Shi et al., 2015; Park et al., 2017). River ice processes were included into LSMs (Park et al., 2016b), which modeled the trend toward shorter ice-cover period and the subsequent warming of river water temperature, consistent with the climate warming (Park et al., 2017). Despite the efforts towards more targeted model development that have been made during the past few decades, models still have limitations and biases in the simulations. However, the models are powerful tools to examine the functioning of the Arctic hydrology system and provide insight on where knowledge is insufficient, motivating past and future research needs (Lique et al., 2016).

The goals of this chapter are to provide an overview of our current knowledge on the functioning of the Arctic hydrology system through modeling perspective and introduce ongoing activities for improving model performance with respect to the various cold region hydrological processes at different time and spatial scales. It also discusses the gaps in our current understanding and the needs and directions of future model developments to better understand the Arctic hydrologic system.

2. Historical background

2.1 Major hydrologic processes in Arctic region

The main hydrological processes in the terrestrial Arctic with implications on freshwater storages and fluxes in the northern region are precipitation, evapotranspiration (ET), surface runoff and channel flows, permafrost and groundwater hydrology, and river and lake ice (Bring et al., 2017a). A substantial proportion of Arctic annual precipitation is falling and stored as snow and released to the river network in a relatively short time window during spring snowmelt. The phase of precipitation and the intensity with which precipitation is delivered influences the water balances and runoff generation. The majority of precipitation over most Arctic basins returns to the atmosphere as ET that links the water and energy cycles and couples the land to the atmosphere. River discharge is the other major water flux out of Arctic basins conveying water, heat, sediments, carbon, and nutrients to the coastal domain and to the Arctic Ocean. Most of the rivers flow to the Arctic Ocean during the spring snowmelt and in summer. Permafrost and its active layer dynamics govern a wide range of surface and subsurface processes across permafrost landscapes and control mechanisms of runoff generation. Due to the large extent of the area underlain by permafrost, the active layer thickness and behavior vary across the terrestrial Arctic region, which influences soil moisture and storage. Seasonal changes in river and lake ice-cover are also prominent features of Arctic freshwater systems. The freshwater ice produces numerous effects on various fluxes and flow dynamics in the Arctic regions.

A number of studies have identified changes in the Arctic freshwater system over the recent decades, as warming climate has caused many changes in the terrestrial Arctic freshwater processes. Earlier snowmelt, decreasing snow extent, permafrost degradation with melting of ice-rich surface, expansion of thermokarst lake, increasing vegetation biomass, and northward vegetation movement are some of the changes observed in the region. These changes are also linked to surface and subsurface hydrological processes and river flows, consequently amplifying the complexity of interaction, and feedbacks between the processes. These complexities in turn make it difficult to precisely predict the magnitudes and directions of future changes in hydrologic processes due to climate warming.

2.2 Observations over the Arctic watersheds

Incomplete knowledge about the magnitude and spatial-temporal pattern of high latitude precipitation has been a big challenge in Arctic hydrologic research over the years and is still a major obstacle to our current efforts to quantify the water and energy budget in the region. The major factors which contribute to uncertainties in the estimation of precipitation in the is the high latitude regions include: sparseness of the precipitation observation networks; uneven distribution of measurement sites, (i.e. biased toward coastal and the low-elevation areas); spatial and temporal discontinuities of precipitation measurements induced by changes in observation methods and by different observation techniques used across national borders, and the biases in gauge measurements, such as wind-induced undercatch, wetting and evaporation losses, and underestimation of trace amount of precipitation (Goodison et al., 1998). Of the above factors, systematic errors in gauge measurements are particularly important, because these biases can reach up to 50-100% of the gauge-measured records at the cold and windy locations (Yang et al., 1998, 1999; Yang, 1999; Yang and Ohata, 2001). In particular, the reduction of observational stations in high latitudes can affect ground-truthing of satellite observations and the quality of reanalysis datasets, which may in turn influences model projections.

Seasonal snow cover over land area of the Arctic is another component of the terrestrial cryosphere that affects hydrology and provides important feedback to regional climate through its high albedo (e.g. Lemke et al., 2007). However, direct snow observations are very limited across large parts of the terrestrial Arctic with the lowest density of observational stations found at the northern part of Canada (Figure 1). This lack of sufficient observing stations limits proper monitor and quantification of trends in snow cover extent, duration and snow depth in the region (Rawlins, et al., 2007), resulting in larger differences in snow amount between satellite observation and model simulation (Figure 1). In Russia, meteorological stations largely increased since 1950, which contributed to improve model simulation for snow depth (Park et al., 2015) and captured the increasing trend of snow depth at the northern Siberia under the condition of warming temperature (Bulygina et al., 2009). However, the subsequent closing of those stations since 1990s coincides with the beginning of significant changes in the Arctic terrestrial processes and landscapes.

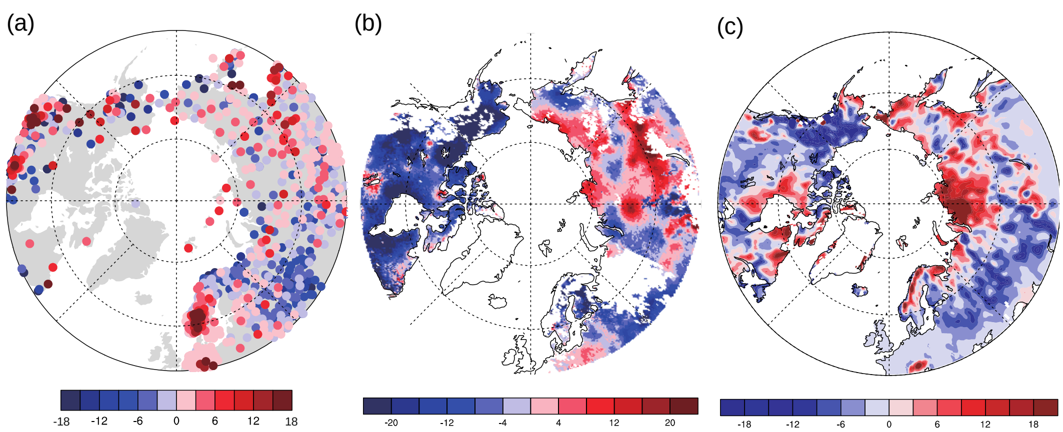

Figure 1. Comparison of decadal anomalies of (a) observed mean winter (DJF) snow depth (cm), (b) mean winter snow water equivalent (mm) provided by GlobSnow, and (c) CHANGE model simulated mean winter snow depth (cm). The anomalies represent differences in 2001–2009 relative to 1991–2000 (Park et al., 2015).

Many river discharge monitoring stations in the Arctic have been closed, resulting in a declining capacity to observe changes in arctic hydrology and northern flowing rivers (Shiklomanov et al., 2006; Déry et al., 2011). Although the reduction in the number of observing stations is followed by specific recommendations on how to modify the monitoring network to make it more efficient (Mishra and Coulibaly, 2010), it affects our capacity to identify where and when the greatest changes in river discharge have occurred. Bring et al. (2017b) developed a methodology to identify where monitoring stations should be placed to observe significant changes in river discharge at the pan-Arctic scale and suggested that central and eastern Siberia, Alaska, and central Canada are hot spots for the highest changes.

2.3 Changes in observed and simulated hydrological processes

Increases in snow depth have been observed over northern Siberia in the recent decades (Bulygina et al., 2009), consistent with model simulation (Park et al., 2015). The increase in snow depth was closely associated with an increase in the early winter precipitation (Park et al., 2013). Some studies suggested that the declining Arctic sea ice has resulted in increased precipitation in the form of snow over the Siberian regions (Ghatak et al., 2010; Cohen et al., 2012). On the other hand, Derksen and Brown (2012) have showed that late spring–early summer (May–June) NH snow cover, which is predominant over the Arctic, decreased significantly over the last four decades. Using the Variable Infiltration Capacity (VIC) model, Shi et al. (2013) have also found that both observed and modeled North American and Eurasian snow cover have statistically significant negative trends from April through June over the period 1972–2006. Holland et al. (2006) found a significantly increasing trend in the ensemble average river runoff to the Arctic Ocean over the twenty century, with the simulated change of 7% increase in the Eurasian runoff; this result is in excellent agreement with the changes during 1936 to 1999 reported by Peterson et al. (2002). Haine et al. (2015) have also reported that the annual Arctic river discharge increased by 300 km^3 during 2000–2010 relative to 1980–2000. The increases include the contribution of the increased snow water, which is reflected by increases in the spring season river discharge (Park et al., 2017). An assessment of the combined daily discharge of Eurasian Arctic rivers also revealed an earlier and higher spring peak discharge in 2015 relative to the 1980–1989 average (Holmes et al., 2015).

However, with simultaneous changes in air temperature (Hinzman et al 2005), precipitation (Yang et al 2003; Rawlins et al 2010), vegetation (Walker et al 2010), and active layer thickness (Zhang et al 2001), and complex interactions among these factors, the actual changes in both the timing and volume of spring streamflow may not be as simple as first expected (Déry et al 2009). For example, some changes could be expected to result in earlier melt and runoff, while others would delay melt and/or runoff. Using five percentile timing measures of springtime streamflow (Figure 2), Shi et al (2015) found a general delay in streamflow timing over a small watershed in northern Canada. However, there are stronger trend signals for the high percentiles (Q90 and Q95) of spring runoff than that for the low and middle percentiles (Q5, Q10, and Q50). The results indicate that the differences are due to the contradictory effects of winter-spring air temperature changes, temperature fluctuation during the melting period, and spring rainfall to spring runoff, in addition to the changes in vegetation. Therefore, the effect of climate change may not be the only dominant factor for the changes in spring streamflow regime. Those advancing melt and runoff may include: earlier snowmelt onset resulting from the warming winter/spring air temperature; warmer soil temperature; and shallow snowpack decreasing water storage supply; while those delaying melts and/or runoff may include: increasing tundra shrub cover that would change snow cover distribution with deeper snow in shrub patches and shrub stems shading the surface and reducing wind speed at the snow surface; deeper active layer resulting in greater soil moisture storage and therefore possibly delaying melt runoff. In addition, changing frequency and magnitude of rain-on-snow events, increases in end of winter snow temperature, hillslope runoff controlled by the refreezing of water in the active layer and the storage capacity of the active layer, and streamflow affected by the occurrence of snow dams (Woo and Sauriol 1981) in the stream channel could be other reasons.

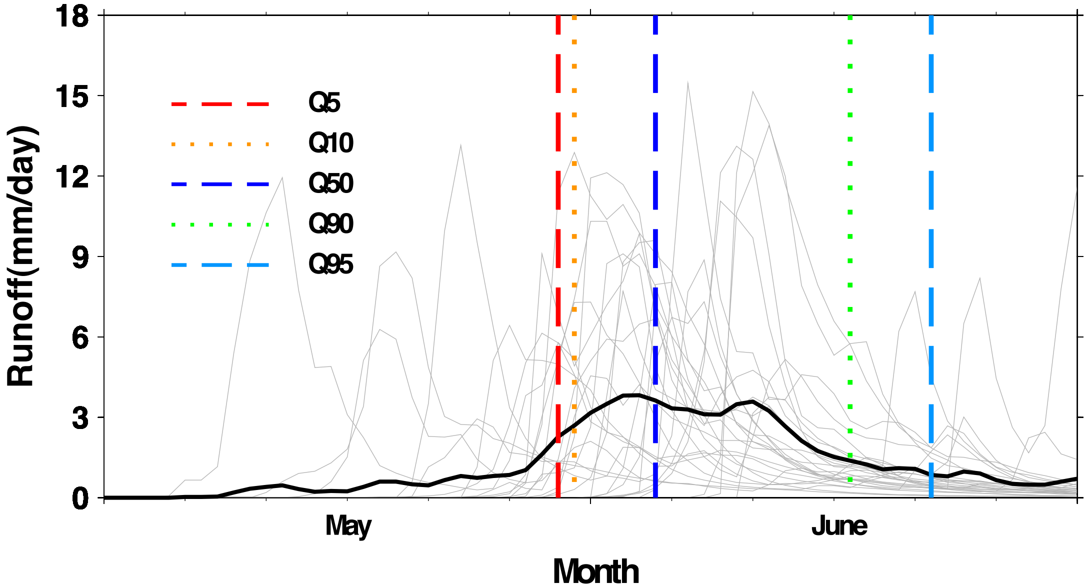

Figure 2. Daily mean runoff (grey lines) for 1985-2011 in Trail Valley Creek, Canada. Five streamflow timing measures (Q5, Q10, Q50, Q90, and Q95) are shown for the spring (May and June) (modified from Shi et al., 2015).

Permafrost has experienced warming and degradation during the past decades due to the combined influences of the increased snow depth and warming temperature. Models have simulated the degradation of near-surface permafrost in the last century over the northern regions (Lawrence et al., 2012; Burke et al., 2013; Park et al., 2015). Deepening active layer thickness (ALT) has been observed at permafrost regions in response to the warming temperature (Park et al., 2016a). The increase in ALT enhances water storage capacity of the soil column, hence temporarily lowering the conversion of soil water into river discharge. On the other hand, later soil freezing and talik formation due to the warming climate would likely increase the connection of soil water to river network during the autumn and winter seasons. Park et al. (2017) examined apparent increases in the Arctic river discharge during the colder months (i.e. October–March), suggesting some implications from the warming permafrost. Tananaev et al. (2016) analyzed permafrost temperature and discharge data in the Lena basin over one century and found higher correlations between winter low flows and air temperature, particularly significant in the southern regions underlain by discontinuous permafrost.

In the Arctic, ET is most active during summer season. Higher summer ET may exceed precipitation, thereby drying soil moisture and lowing contribution of precipitation to river discharge (Park et al., 2008). The warming climate could further reduce the contribution because of increasing ET as it has higher positive correlation with temperature. A process-based land surface model, CHANGE (Park et al., 2011), simulates the increase of ET over the terrestrial Arctic during the period of 1979–2016 (Figure 3). The increase is significant since 2000 when the warming of air temperature was stronger. The increase in simulated ET of 6.3 mm dec^{-1} is comparable to 3.8 mm dec^{-1} of satellite-derived estimation (Zhang et al., 2009). While the influences of soil moisture produced by the degradation of ice-rich permafrost on ET have been highlighted; however, they have not yet been quantitatively assessed.

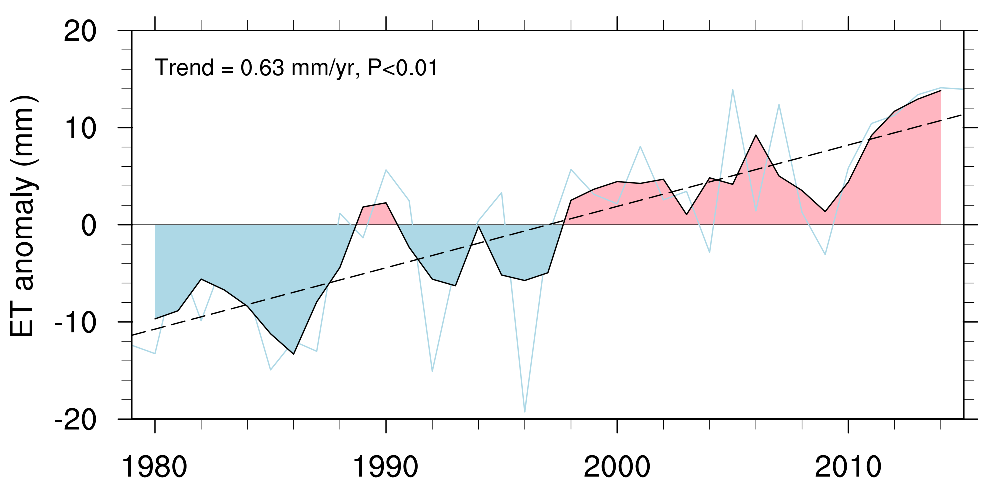

Figure 3. Inter-annual variability and trend (dashed line) in annual total evapotranspiration anomaly simulated by CHANGE over the pan-Arctic terrestrial region. The dark line represents 3-yr running means of the annual anomaly (light blue line) of the evapotranspiration.

3. Brief descriptions of major cold region hydrologic models

All mathematical models are by necessity simplifications of complex systems and, as such, they can omit or simplify different processes of relevance to a specific problem. Cold region land surface processes such as sublimation from blowing snow, surface storage in large lakes and wetlands, including those seasonally frozen, and infiltration limitation by frozen soils are still not well represented in some land surface schemes of large scale models (Bowling et al., 2000; 2003a). For example, Slater and Lawrence (2013) assess the ability of the latest generation of land surface schemes to simulate present day and future permafrost of the terrestrial Arctic and concluded that most of the models still contain structural weaknesses that limit their skill in simulating cold region subsurface processes. While there is a substantial progress in understanding each of these important cold region processes, there is also a lag in up-scaling and incorporating the latest process understanding into the land surface schemes of large-scale models. Moreover, large-scale models are run at quite coarse resolution (~1 to 10 km) and may not resolve some processes of importance to Arctic hydrology. For example, topographic controls on precipitation are often not well simulated, leading to biases in the regional characterization of rain and snowfall (e.g. Finnis et al., 2008).

One of the most widely used large-scale, cold region models is the Variable Infiltration Capacity (VIC) model. VIC is a semi-distributed macroscale hydrological model (Liang et al., 1994, 1996), which parameterizes the dominant hydrometeorological processes at the land surface-atmosphere interface and solves both surface water and energy balances over a grid mesh. Distinguishing characteristics of the VIC model include: subgrid variability in land surface vegetation classes; subgrid variability in the soil moisture storage capacity; drainage from the lower soil moisture zone (base flow) as a nonlinear recession. To simulate streamflow, VIC results are typically post-processed with a separate routing model (Lohmann, et al., 1996; 1998) based on a linear transfer function to simulate the streamflow. The critical elements in the model that are particularly relevant for implementation in cold regions include a two-layer energy balance snow model (Cherkauer and Lettenmaier, 1999), frozen soil and permafrost algorithm (Cherkauer and Lettenmaier, 1999, 2003), blowing snow algorithm (Bowling et al., 2004), and effects of lake and wetlands on moisture storage and evaporation, which are particularly important for runoff at high latitudes (Bowling et al., 2003a). VIC has participated in the WCRP Intercomparison of Land Surface Parameterization Schemes (PILPS) project and the North American Land Data Assimilation System (NLDAS), where it has performed well relative to other schemes and to available observations (Bowling et al, 2003b; Lohmann et al., 2004; Nijssen et al., 2003). Consequently, VIC has been used to conduct hydrologic studies over the Pan-arctic region (Su et al., 2005, 2006). The VIC model included lake and wetland algorithm, and a simulation of runoff from Putuligayuk watershed on the Alaskan arctic coastal plain indicated that up to 80% of snow meltwater did go into storage each year, meaning temporarily negative contribution to streamflow (Bowling and Lettenmaier, 2010). A major ability of VIC can calculate the global freshwater discharge to the oceans. The VIC model estimated that discharge from Eurasian rivers portioned 37% of flows to the world oceans (Clark et al. 2015).

The coupled hydrological and biogeochemical model (CHANGE, Park et al. 2011) is another process-based cold region model that is combined with sub-models of soil thermal and hydrologic states, snow hydrology, and plant stomatal physiology and photosynthesis to calculate heat, water, and carbon fluxes in the atmosphere-land system. The model solves the heat and hydraulic conduction equations and represents permafrost dynamics including an explicit treatment of soil freezing/thawing phase changes. The snow sub-model includes energy and mass budgets to express changes of heat and water contents in the snowpack, so that it simulates snow accumulation and snowmelt at the land surface. The vertical water flux between soil column layers is solved by Darcy's law. Excess water at the soil surface is determined as surface runoff. At the bottom soil layer, the excess moisture is defined as subsurface runoff that flows to the river network. If permafrost is present within the soil column, water infiltration to lower soil layers is considerably impeded, which is calculated by a parameterization representing the ice impedance. The excess water at the permafrost layer is substituted to subsurface runoff. CHANGE couples the river routing scheme TRIP2 (Total Runoff Integrating Pathways) to represent basin runoff routing and river discharge dynamics (Park et al. 2016b). Surface and subsurface runoffs calculated by CHANGE are directly passed to individual storage reservoirs of TRIP2, in which water is routed to the river mouth through a prescribed channel network. The discharge processes consider the contribution of groundwater to streamflow, which is represented by a linear function of outflow with a groundwater delay parameter. The discharge scheme also includes stream temperature model where water temperature (T_w) is calculated based on the inflow of upstream heat into the stream segment within the drainage network, the dominant heat exchange at the air–water surface, and the inflow of heat and water from tributaries (Park et al. 2017). The calculated T_w is also used to simulate river ice thickness on the basis of heat exchanges between atmosphere–snow–ice–frazil ice–water boundaries (Park et al. 2016b).

The Community Land Model (CLM4) (Lawrence et al., 2011), on the other hand, is the land component of the Community Climate System Model (Gent et al., 2011) that simulates water, energy, and carbon fluxes in the atmosphere–vegetation–soil system, and the export of freshwater to the oceans using a streamflow routing sub-model called the River Transport Model (RTM). Each grid runoff calculated by CLM4 is transported to the oceans along the river network by RTM based on linear reservoirs (Oleson et al., 2010). The presence of frozen surface soils and permafrost front reduce infiltration rates of soils with high ice contents in such a way that much of the snowmelt water and rainfall can be converted to runoff. The impedance effect of ice on water is expressed by the soil hydraulic properties in the model, thereby improving the runoff hydrographs and soil moisture profiles (Swenson et al., 2012).

Another cold region hydrologic modeling approach for simulation of river discharge by combining land surface model and streamflow routing model is that of the Joint UK Land Surface Simulator (JULES) (Finney et al., 2012) and Jena Scheme for Biosphere–Atmosphere Coupling in Hamburg (JSBACH) model (Ekici et al., 2014). JULES contains a version of TOPMODEL to account for sub-grid heterogeneity of soil moisture using surface topography within the calculation of surface and subsurface runoff. The influence of frozen soils on the hydraulic conductivity is also included in JULES in the same way as it is represented in CHANGE and CLM4. JSBACH also represents freeze/thaw processes coupling hydrological processes in a layered soil scheme.

4. Current research and model applications

4.1 Factors affecting cold-region hydrologic modelling

Most cold-region land surface models represent the process of phase change to correctly simulate permafrost dynamics, including effects of soil organic carbon on soil thermal and hydraulic properties and vegetation dynamics. The models should be able to simulate permafrost degradation and the deepening active layer thickness under a warming climate. While the directions of simulated changes are generally consistent between models, their magnitudes usually have quite larger differences. This is mainly because of the differences in model structures, parameters, forcing data and possibly the depth of the bottom soil boundary that the models define for the simulations. For example, most of the models that had participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5) confined the bottom boundary to a depth of <15 m, simulating permafrost extents for the year 2005 ranging between 1.4 and 17.4 million km^2 (Koven et al., 2013). Larger soil depth reduces the heat conductive rates from the surface, consequently limiting the speed of permafrost degradation. Alexeev et al. (2007) suggested that a soil depth of at least 30 m is needed to simulate annual and decadal cycles of temperature dynamics for the permafrost. A simulation experiment conducted by setting the lower soil boundary to 3.6 m and 50.5 m reported the early twenty-first century near surface-permafrost areas of 1.2 and 2.9 million km^2, respectively, for the two experiments (Park et al., 2015). This difference emphasizes that a shallower soil boundary could underestimate the permafrost extent, which can inductively increase uncertainties of permafrost-associated interactions and feedbacks.

The quality of the forcing data is probably the primary source of uncertainty in model simulation; in particular, simulation results are greatly dependent on the quality of precipitation. In the Arctic rivers, a considerable amount of the discharge is generated from southern mountainous regions. The quantity of mountainous precipitation is characterized by high negative biases that may result in underestimation of the discharge. Adam et al. (2006) produced a bias-corrected global precipitation dataset, separating mean monthly catch ratios for rainfall and snowfall and also adjusting precipitation for orography effect.

Simulation of the VIC model using the bias-corrected precipitation exhibited appropriate model performance for the seasonal and inter-annual variations of the discharge over the pan-arctic land area, highlighting the precipitation-related uncertainties in simulating for Arctic river discharge (Su et al., 2005). Tian et al. (2007) conducted model simulations forced with and without precipitation-bias corrections from 1973 to 2004 and found that the enhanced snowfall induced by the bias corrections increased streamflow by 5–25% for most major rivers in the northern latitudes.

Cold region land surface processes such as sublimation from blowing snow, surface storage in large lakes and wetlands, including those seasonally frozen, and infiltration limitation by frozen soils are still not well represented in some of the large scale cold region hydrologic models (Bowling et al., 2000, 2003a). Hostertler et al. (2000) developed a model for multiple lakes within one grid cell representing dynamic lake area as a function of water storage. The model was further improved the storage dynamics as linking directly lakes to the channel network (Gao et al., 2011). However, most of models don't yet include the processes of lake and wetland. This deficiency tended to reproduce seasonal hydrographs deviated from observations, peaking too much in spring, especially in Ob and Mackenzie rivers (Slater et al., 2007) where a large proportion of the of basin area (11 % for Ob and 49 % for Mackenzie) is covered by lakes and wetlands that can temporarily store snow-melted water in the spring, reducing runoff and peak discharge rates. The fifth generation Canadian Regional Climate Model (CRCM5) coupled a one-dimensional lake model included interflow, i.e. lateral flow of water in the soil layers (Huziy and Sushama, 2017). Comparison of CRCM5 simulations with and without lakes suggested that adding the interflow process leaded to increased streamflow during summer and fall seasons for the majority of the northeast Canadian rivers.

4.2 Recent improvements in representing cold region hydrological processes

As an important component of cold regions processes, frozen soil infiltration plays a very dominant role in the hydrology of the terrestrial Arctic regions. Both seasonally frozen ground and permafrost directly affect infiltration while they indirectly affect the heat transfer to and from the overlying snowpack (Kane and Chacho, 1990). To improve spring peak flow predictions, the VIC model has developed a parameterization of the spatial distribution of soil frost (Cherkauer and Lettenmaier, 2003). Adam (2007) described some significant modifications to the frozen soil algorithm, including the bottom boundary specification, the exponential thermal node distribution, the implicit solver using the Newton-Raphson method, and an excess ground ice and ground subsidence algorithm. This is good for simulating permafrost, for which it is often necessary to specify a maximum depth of as much as 30 m (Alexeev et al., 2007). By adding the ice content component in the heat flux equation, the impact of frozen soil on moisture transport can be simulated by the moisture flux algorithm. One way the ice content in the frozen soil affects the moisture transport is through available moisture storage. Each of the three soil layers in VIC is divided into thawed, frozen, and unfrozen sublayers. The thickness of these sublayers depends on the soil temperatures at the nodes. When there is a frozen layer present, the ice content is based on the average temperature of the sublayer. The second way the ice content affects soil moisture transport is through its effect on infiltration and drainage. When a soil layer has high ice content, it will be nearly saturated to the runoff calculations; but at the same time, there is little moisture that can be allowed to drain to the lower layer. The model implementation for permafrost by Shi et al. (2016) uses a depth of 15 m with 18 soil thermal nodes exponentially distributed with depth and a no flux bottom boundary condition. When the no flux bottom boundary condition is selected for the soil column, the VIC model solves the ground heat fluxes using the finite difference method. This means that the soil temperature at the bottom boundary can change, but there is no loss or gain of heat energy through the boundary. To evaluate the model ability to replicate observed trends in frozen soils simulations, Figure 0-4 compares modeled and observed soil temperature anomalies averaged over 146 observation sites across the former Soviet Union for the period of 1970-1990 at the depths of 0.2 m, 0.8 m, 1.6 m, and 3.2 m, respectively. The results reveal that the model captures the interannual variability of the soil temperature dynamics. In addition, Figure 4 also shows the correlation coefficients between modeled and observed time series for the period from 1970 to 1990. The VIC and observed soil temperature time series at 0.2, 0.8, 1.6, and 3.2 meters are highly correlated (two-sided $p < 0.01$), indicating that VIC is able to reproduce soil temperature profiles and provides a surrogate for scarce observations for estimation of long-term changes in permafrost at high latitudes.

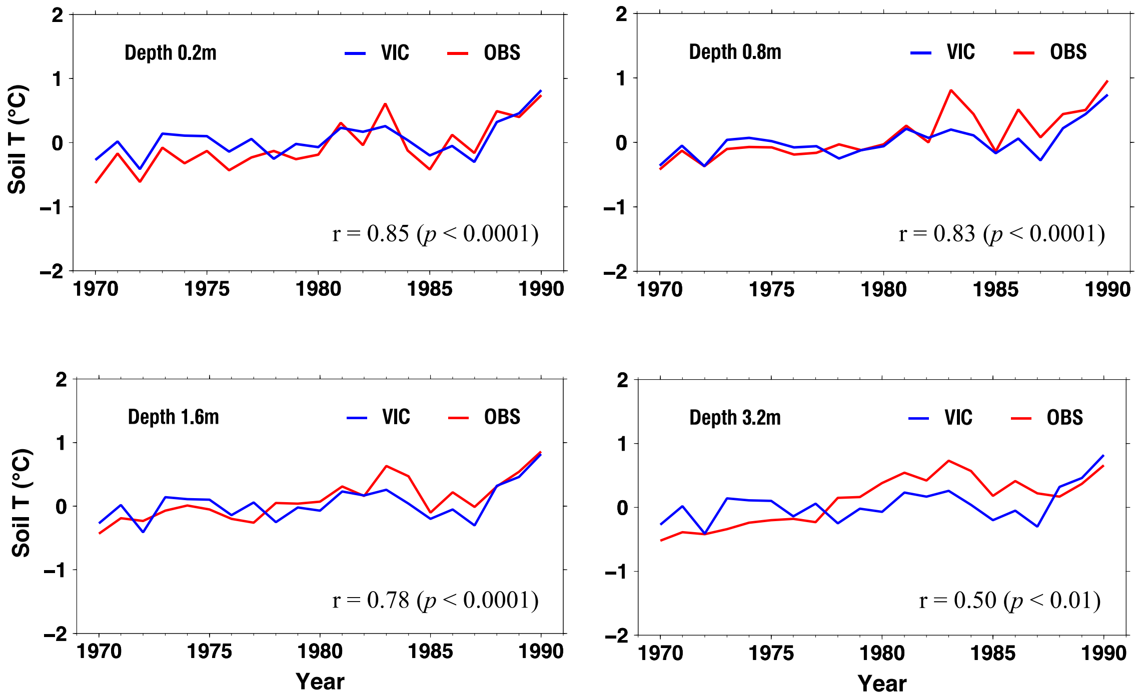

Figure 4. Comparisons between observed and modelled soil temperature anomalies averaged over 146 observation sites across the former Soviet Union for the period of 1970-1990 at the depths of 0.2 m, 0.8 m, 1.6 m, and 3.2 m, respectively. The correlation is statistically significant at a level of $p < 0.025$ (from Shi et al., 2016).

Lakes are other important component of the terrestrial Arctic drainage basins through the storage and flux exchange of heat and moisture that are affected by the presence and nature of snow and ice cover. Similarly, most Arctic rivers are ice-covered for significant part (six to eight months) of the year and the freezing and breakup of river ice-cover significantly affect the magnitude of discharge and water levels throughout the river system. There is a significant growth in the study of lake and river-ice modelling in recent years, though mostly at local scale. However, lake and river ice processes are rarely included in cold region hydrologic models (Ma and Fukushima, 2002). Recently, the CHANGE coupled a river ice model into the river routing and discharge model, enabling explicit representation of river ice and water temperature dynamics based on surface energy exchange with the atmosphere (Park et al., 2016b). The simulated mean total Arctic river ice volume was 54.1 km^3 based on the annual maximum ice thickness, while the volume decreased by 2.8 km^3 over the period of 1979–2009 in response to the warming air temperature. Brooks et al. (2013), using a degree-day ice growth model, estimated January peak river ice volume of 140km^3 over the Northern Hemisphere, and reported a decreasing trend in the estimated ice volume during 1957–2002 (-0.075 km^3 yr^{-1}). A lake-ice modelling study by Dibike et al. (2011), using a one-dimensional lake simulation model, also indicated that future warming will result in an overall decrease in lake ice-cover duration by about 15 to 50 days and maximum lake-ice thickness by about 10 to 50 cm, on average, by the end of this century. A one-dimensional dynamic lake model was also implemented for simulating small lakes within a land surface scheme of a Canadian regional climate model (MacKay 2012). This model is based largely on well-established process algorithms and a complete nonlinear surface energy balance including turbulent mixing in the surface mixed layer. However, this approach is still not implemented in any of the uncoupled land surface schemes and cold region hydrologic models.

The Arctic rivers are frozen during the winter, which decreases heat exchanges with the atmosphere. The ice formation reduces water storage within the river channel, and thus decreases the winter low flow. When the river ice is melted, the energy exchange between the river surface and atmosphere becomes strong. The river water temperature is warmer and reaches the maximum value in summer season alongside the seasonal variation of air temperature. Models that had considered the heat exchanges between the river surface and atmosphere and the heat movement from upstreams well simulated the seasonal and interannual variability of water temperature in the Arctic rivers (van Vliet et al., 2012; Park et al., 2017). Model simulation results by Park et al. (2017) indicated a warming trend of river water temperature by 0.16℃ dec^{-1} at the outlets of the pan-Arctic rivers, including widespread spatial warming consistent with the warming air temperature. The warming of water temperatures in the Arctic rivers induced by climate warming suggests the supply of warmer freshwater along with increasing river discharge (Figure 7) result in an overall increase in heat supply to the Arctic Ocean. This change in river heat flux would most likely impact seasonal sea ice retreat and the warming of sea waters along the shelf regions.

The CHANGE model simulation show increase in winter snow depth since 1901 and deeper snow after 1980 (Figure 5). Large differences in snow depth between the observation and simulation are found for the period before 1960, which is likely attributable to the small number of available observation stations during that period. Since 1960, the simulated anomalous snow depth displays a similar time series with the observation (r=0.38, p<0.1). The higher level of snow depth since 1970 is probably due to relatively large contribution of the increased snow over Eurasian region (Bulygina et al., 2009; Park et al., 2013). The increase of the Eurasian winter snow was closely correlated to the increase of snow in the autumn and early winter season (Park et al., 2015). Observations had captured wetting surface humidity in the autumn at the northern Siberia regions (Cohen et al., 2012). The increased snow depth contributed to permafrost warming trough the higher insulation (Park et al., 2015) and the decrease of river ice thickness (Park et al., 2016b).

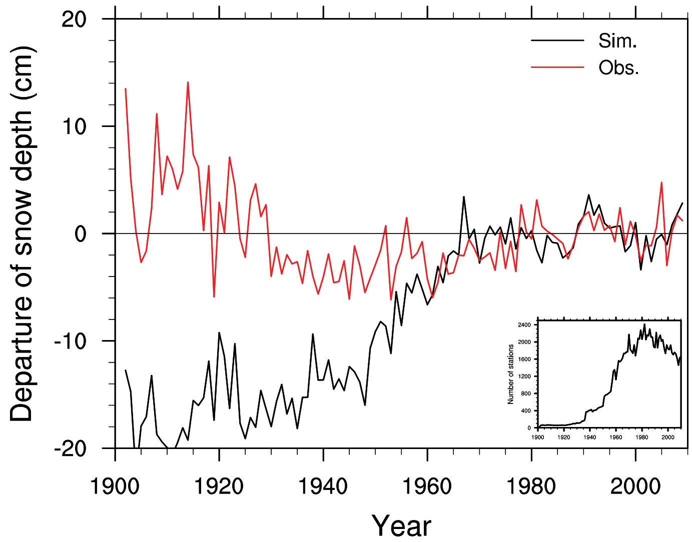

Figure 5. Comparison of interannual anomalies (relative to 1971-2000) between observed and simulated winter snow depths over the pan-Arctic terrestrial region. The inner graph represents the number of observation stations used for the analysis (modified from Park et al., 2015).

Long-term monitoring of river discharge and water chemistry in northern basins is essential for identifying and understanding changes in the Arctic freshwater system. However, the simultaneous observations are not common in the Arctic regions. As a result, the long-term water chemistry in the Arctic are considerably rare relative to the discharge. Only recently, parallel sampling programs, called as the Pan-Arctic River Transport of Nutrients Organic matter and suspended Sediments (PARTNERS) project in 2003 and continued as the Arctic Great Rivers Observatory (Arctic-GRO) in 2008, have been operated on the Arctic major rivers (Tank et al. 2012; McClelland et al., 2015). Results of the projects contributed to capture characteristics of seasonal and geographical variations in water chemistry that is associated with watershed properties. This knowledge has established a framework for tracking future changes in river hydrological processes through the water chemistry. However, model developments on the river water chemistry are considerably delayed relative to the river discharge models. Very few studies have therefore provided quantitative assessments of changes in water chemistry in Arctic rivers, addressing the potential changes caused by the warming climate. Li Yung Lung et al. (2018) assessed the chemical composition of a broad suite of rivers draining to the Canadian Arctic Ocean and Hudson Bay using previously observed data. However, they found larger data gap in the observations and suggested a modeling approach to extrapolated the fluxes to the full Canadian Arctic drainage basin.

4.3 Freshwater inflow to the Arctic Ocean

Historically, observations have indicated increases of discharge over much of the pan-Arctic (Peterson et al., 2002, 2006; Shiklomanov and Lammers, 2009). In particular, the annual flow during

2000–2010 has increased by about 300 km^3 relative to the 3900 km^3 during 1980–2000 (Haine et al., 2015). The Russian river discharge, constituting about 80% of the Arctic discharge, increased 3.0 $km^3\ yr^{-1}$ during the same period, which is comparable to the increase 2.9 $km^3\ yr^{-1}$ from the major Russian rivers over 1936–2008 (Shiklomanov, 2010). Discharge from North America northern rivers shows insignificant increase; earlier studies reported decreasing flows for North America high latutudes (Déry and Wood, 2005), while recent analyses suggest flow increases (Ge et al., 2013; Déry et al. 2016). The VIC model with cold region land process updates was applied to the entire pan-Arctic domain at a 100-km to evaluate the representation of Arctic terrestrial hydrologic processes and to provide a consistent baseline hydroclimatology for the region (Sue et al., 2005). The model simulations of key hydrologic processes for the periods of 1979–1999 were evaluated using streamflow records, snow cover extent, dates of lake freeze-up and break-up, and permafrost active-layer thickness. The pan-Arctic drainage basin was partitioned into 12 regions for model calibration and parameter transfer according to geographical definitions and hydroclimatology. Twenty-seven individual sub-basins within different regions were chosen for model calibration and validation. Results indicated that the VIC model was able to reproduce the seasonal and interannual variations in streamflow quite well (for 19 basins out of 27 monthly Nash efficiency exceeded 0.75, and for 13 it exceeds 0.8) (Figures 6). However, comparison of multi-model simulations of the pan-Arctic river discharge shows large deviation from the observations, particularly in the spring peak discharge with earlier timing and larger amount (Slater et al., 2007). The deviation was later improved by coupling river ice processes to the discharge model where the breakup of river ice in the spring causes the delay of snowmelt-peak discharge and underestimate the flow volumes, thus improving the seasonal variability of discharge in model simulations (Park et al., 2016b). Swenson et al. (2012) also improved the parameterization of the hydraulic properties of frozen soil limiting the infiltration of soil water, which increased summer discharge in two large Siberian rivers compared to simulation results without the parameterization.

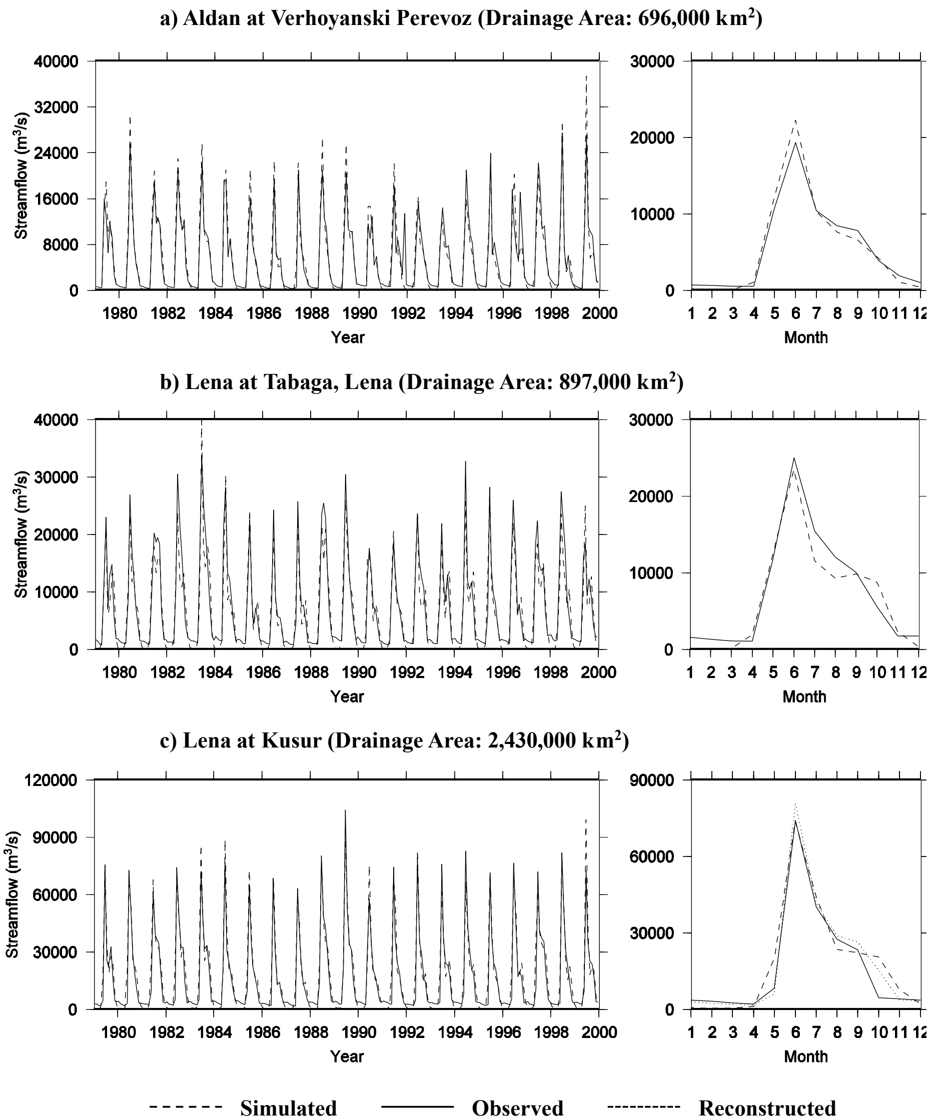

Figure 6. Observed versus VIC simulated hydrographs at three locations within the Lena River basin:(a) Aldan at Verkhoyanskiy Perevoz, (b) Lena at Tabaga, and (c) Lena at Kusur (the mouth of the Lena River). The left column of the figure presents time series of monthly streamflow for 1979–1999, and the right column of the figure displays mean monthly streamflow for 1979–1999 (modified from Su et al., 2005).

The discharge simulated by the VIC model at the farthest downstream sites were used to estimate the total circumpolar river inflow to the Arctic Ocean. As such, a 21-year (1979–1999) average river inflow to the Arctic Ocean was estimated as 3,354 km^3 /year; and 3,596 km ^{3}/year with the inclusion of the Canadian Archipelago. On the other hand, the total Arctic discharge, excluding the Yukon River, simulated by the CHANGE model over 1979–2013 was averaged to be around 3,717.3 km^3 yr^{-1} (Figure 7), which is comparable with the VIC simulation and 3,900–4,200 km^3 yr^{-1} for the observation over 1980–

2010 (Haine et al., 2015). The differences in the annual Arctic river discharge between observation and simulation are attributable to the different estimations of discharges from the Canadian Arctic Archipelago and Baffin Bay that have lower observational stations. Haine et al. (2015) estimated the annual discharge of 500 km^3 for this region, while models (e.g., VIC and CHANGE) simulated 250–300 $km^3\ yr^{-1}$ (Su et al., 2005; Park et al., 2017). The relationship between the inflow volume and contributing area resulting from various data sources and VIC simulations indicated that the VIC model was comparable to the previous estimates derived from the observed data (Su et al., 2005). However, the wide range of Arctic freshwater discharge estimates, when adjusted for differences in drainage areas, were quite similar despite of the differences in drainage areas used in the individual studies.

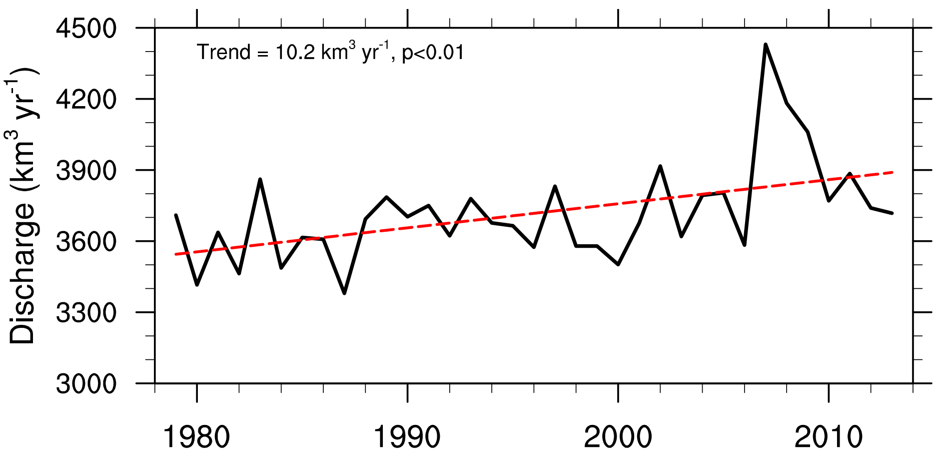

Figure 7. Interannual variability and trend (dashed line) in total annual discharge at the outlets of Arctic rivers, simulated by the CHANGE model.

4.4 Long-term hydrologic model simulations of pan-Arctic river basins

Using the Variable Infiltration Capacity (VIC) macroscale land surface model forced with gridded climatic observations, Shi et al. (2013) have reproduced spatial and temporal variations of snow cover extent (SCE) reported by the National Oceanic and Atmospheric Administration (NOAA) Northern Hemisphere weekly satellite SCE data. They have found that both observed and modeled North American and Eurasian snow cover in the pan-Arctic have statistically significant negative trends from April through June over the period 1972–2006. A number of studies (Bowling et al 2000; Rawlins et al, 2003; Su et al, 2005) have also demonstrated the potential of different cold-region hydrologic models to reproduce seasonal variations in freshwater discharge to the Arctic. However, results from multi-model simulation of pan-arctic hydrology by Slater et al (2007) showed up to 30% difference in annual partitioning of precipitation between evaporation and runoff over a major Arctic watershed such as the

Lena. Therefore, there seems to be still more work to be done in terms of both good quality forcing data and improved parametrization of land surface processes to arrive at a better model estimates of the historical variability and change within terrestrial components of arctic freshwater system. Similarly, the CHANGE model simulates an increasing trend (10.2 km^3 yr^{-1}, $p>0.1$) of the entire Arctic river discharge over the past four decades (Figure 7), consistent with the increasing precipitation under the warming climate. The combination of observations and general circulation models estimated a positive trend of 5.3 km^3 yr^{-2} for annual pan-Arctic discharge from 1950 through 2004 (Rawlins et al., 2010). A synthesis for earlier simulations with global hydrological models, with inputs from climate models, estimated overall increases of 10–20% over the pan-Arctic rivers (Walsh et al. 2005). Recent such simulations generally show increases on the order of 25–50% (Shiklomanov et al. 2013; van Vliet et al. 2013; Koirala et al. 2014). Decreases are mostly concentrated to the southern interior of the pan-Arctic drainage basin (van Vliet et al. 2013; Koirala et al. 2014).

Using future climate projections from six climate models and two emissions scenarios and a macroscale hydrological model, Arnell (2005) has found increases of up to 31% in river inflows to the Arctic by the 2080s under high emissions and up to 24% under lower emissions, with large differences between models. He has also demonstrated that future runoff projection using such uncoupled model is more sensitivity to the input data used to drive the models than to the terrestrial hydrologic model form and parameterization. The sign of projected changes of seasonal snowfall and snow water equivalent (SWE) with respect to the present is spatially variable as it depends on the present local climate conditions: in very cold regions, climate warming will lead to overall increased winter snowfall due to increased winter precipitation and thus to a thicker snow cover, while in warmer regions, the higher temperatures will lead to the opposite (Raisanen, 2008). However, other snow-related variables, such as snow cover extent (SCE), exhibit a more direct relationship to temperature. Under CMIP3 B2 scenario of climate change, a regional climate model coupled a large-scale hydrological model simulated a 25% increase in the future freshwater runoff from rivers in Northern Europe to the Barents Sea (Dankers and Middelkoop, 2008). As the snow season is 30–50 day shorter, the simulation revealed the shift of about 2–3 weeks in the spring discharge peak.

5. Future research needs

While there is a substantial progress in understanding important cold region processes (e.g., sublimation from blowing snow, permafrost degradation and surface storage in lakes and wetlands, infiltration in frozen soils, etc.), there is a lag in up-scaling and incorporating the latest process understanding into the cold region hydrologic models. The long-term impact of permafrost degradation on local and regional hydrology is poorly understood, but is absolutely critical in terms of predicting future Arctic soil moisture states and river discharge and associated changes in biogeochemical cycling (Holland et el., 2007). The frozen soil and presence of permafrost reduce infiltration rates of snow-melted water and rainfall, consequently increasing surface runoff in the spring and subsurface drainage runoff. The impedance effects of permafrost were parameterized, and the models coupling the parameter generally simulated the observed Arctic river discharges (Swenson et al., 2012; Park et al., 2016b). On the other hand, the warming climates derive the melting of the ice rich surface permafrost, subsequently forming thermokarst lakes. Observations identified the expansion of the thermokarst lake under the recent warming climates (Ulrich et al., 2017). Models physically represented the processes that form thermokarst lakes and subsidence of the ground surface following thawing of ice-rich soil (Lee et al., 2014; Westermann et al., 2016). The improved model had applied to the pan-Arctic scale and addressed that the expansion of thermokarst lakes are effective to more releases of carbon dioxide and methane to the atmosphere, enhancing positive feedbacks to the climate changes (Lee et al., 2014). Furthermore, the channeling between thermokarst lakes formed during the melting makes it easy the transport of lake water to river network (Turner et al. 2014; Ala-aho et al. 2018). This process likely affects river discharge at smaller or local scale, but is uncertain at larger scale.

One other area that need more research effort in cold-region hydrologic modelling is on how to get more representative precipitation data over the Arctic terrestrial watersheds. The difficulty to estimate the magnitude and special variability of cold season precipitation because of the uncertainty in snowfall measurement at high latitude resulting from gauge undercatch of solid precipitation, low precipitation amounts, sparsely distributed observations with the location of observing stations mostly biased toward low elevations and coastal regions, and rare long-term records, are some of the challenges that should be addressed by exploring new approach including enhancing methods to assimilate remote sensing products. (Behrangi et al. 2018; Serreze and Hurst, 2000; Adam and Lettenmaier 2003; Yang et al. 2005).

The warming climates are effective to higher photosynthesis by vegetation, increasing the biomass productivity. The vegetation growths can both intercept more precipitation and access to soil waters produced by the permafrost thawing, consequently reducing the contribution rates of both permafrost-induced water and precipitation to river discharge. Model experiments based on various scenarios can provide quantitative values involving changes in water cycle/budget following ecosystem changes in the context of the warming climates. However, most models have a consistent deficiency in representing the physical processes of the ground ice in permafrost, as mentioned before. Therefore, even though river discharge is increased under the permafrost change, the deficiency makes it hard to separate the contribution rate of the permafrost-induced water to the discharge. This is because the increase of discharge includes the contribution of precipitation that is projected to be increased under the warming climate. A useful way to solve this problem is to incorporate isotope module into the models that can simulate a back trajectory to sources of the discharged water.

The recent warming temperature resulted in the earlier melting of the Arctic river ice. Models well reproduced the changes in the observed river ice phenology (Park et al., 2016b). When river ice is broken in the spring, the broken ice gradually melts as it flows down the river. In the process that ice floes move downstream, ice jam occasionally occur and can induce flooding. Although most models have still considerable deficiency in describing the ice jam, there were efforts of model development to project ice jam flooding in northern rivers (Lindenschmidt et al. 2012; Eliasson and Gröndal 2018). One of the biggest issues in the Arctic terrestrial regions is to know when and where ice jams form and release, because the ice-induced hazards greatly affect people's life in the Arctic community (Rokaya et al. 2018). The projected changes in future climate are big enough to alter the ice jam processes and the severity of breakup event. Therefore, more improvements are needed in representing ice-jam-related processes in cold region models. Moreover, the Arctic rivers convey heat and geochemical constituents to the Arctic Ocean and influence sea ice and biogeochemical dynamics. Observations estimated the total river delivery of nutrients, sediment, and carbon under the current climate (Holmes et al., 2011; Tank et al., 2012). Frey and McClelland (2009) highlighted linkages between permafrost changes and the Arctic river biogeochemistry, because the warming-induced permafrost changes could influence the delivery of biogeochemical constituents. There is also a real possibility that the Arctic freshwater system is likely to undergo transition from a surface water to a groundwater dominant as the result of permafrost thawing (e.g., Brutsaert and Hiyama, 2012). However, models representing the river conveyance of biogeochemical constituents in the Arctic are still insufficient and incomplete. In general, more research is needed towards better understanding and representation of all the different cold-region processes.

6. Conclusion

The hydrological system of cold regions is represented by the unique seasonality; the freezing of the cold season increases the terrestrial water storage as snow and ice, while the melting and thawing as a result of warmer temperature produce larger fluxes of water and heat during the summer season. Those fluxes are further amplified by the warming climate, which subsequently results in changes in the Arctic hydrological processes, such as earlier timing of peak river discharge by earlier snow melt, increasing active layer, and earlier greening with higher vegetation productivity. These changes have certain influences on the freshwater and biogeochemical cycles in the Arctic system with considerable climate implications, ultimately impacting human life in the Arctic regions. This also indicates the need for increased understanding of the changes that are happening in the Arctic hydrological system. However, we are still lacking detailed knowledge of some cold region processes to have a comprehensive picture on how the Arctic hydrologic system respond to the projected change in climate and increased anthropogenic activities across the terrestrial Arctic regions. As an example, operation of dams constructed in the major Arctic rivers has changed the seasonality of discharge; control of flow during spring and early summer has reduced peak discharge, while release of water from the reservoirs has increased discharge during winter (Ye et al. 2003; McClelland et al. 2004). Construction and operation of dams likely enhance evaporation from reservoir surfaces and water usages for agricultural and municipal practices. Climatic warming may increase such water loss. Knowing how the missing water does affect the Arctic hydrologic system is an important concern in the future climates (McClelland et al. 2004).

Land surface models that are based on physical, hydrological, and biogeochemical principles are useful tools that can increase our understanding for the Arctic hydrological system across time and space, through various experimental designs and analysis. Although the models have different levels of complexity and coupled interactions, the simulation results at pan-Arctic scale generally show similar trends in most of the hydrological processes that are consistent with observations. The models project permafrost degradation and the subsequent more vigorous hydrological cycle caused by a warmer and wetter surface. However, the magnitude of permafrost degradation shows large variability between the models due to differences in model structure, parametrization, etc. This variability further increases the uncertainty in the models' projection of the other related processes (e.g., freshwater discharge and biogeochemical cycles), indicating a need to further improve those model processes. As discussed above, model improvement works have been conducted on many aspects of cold region hydrology, including the incorporation of new components and new feedback and interactions (e.g., Swenson et al., 2012; Lee et al., 2014). However, the models still have uncertainty that needs further improvement. For continued progress in understanding the Arctic hydrological system, future research should include the use of innovative strategies, such as the incorporation of assimilation of satellite data within hydrological models (e.g., Lique et al., 2016), more widespread use of multi-model ensembles, parameterization development through better collaboration between the observational and process modeling community, and development of high quality forcing dataset.

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