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Climate-phenology-hydrology interactions in northern high latitudes:

assessing the value of remote sensing data in catchment ecohydrological

studies

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Abstract: We assessed the hydrological implications of climate effects on vegetation phenology in northern environments by fusion of data from remote-sensing and local catchment monitoring. Studies using satellite data have shown earlier and later dates for the start (SOS) and end of growing seasons (EOS), respectively, in the Northern Hemisphere over the last 3 decades. However, estimates of the change greatly depend on the satellite data utilized. Validation with experimental data on climate-vegetationhydrology interactions requires long-term observations of multiple variables which are rare and usually restricted to small catchments. In this study, we used two NDVI (normalized difference vegetation index) products (at ~25 & 0.5 km spatial resolutions) to infer SOS and EOS for six northern catchments, and then investigated the likely climate impacts on phenology change and consequent effects on catchment water yield, using both assimilated data (GLDAS: global land data assimilation system) and direct catchment observations. The major findings are: (1) The assimilated air temperature compared well with catchment observations (regression slopes and R^2 close to 1), whereas underestimations of summer rainstorms resulted in overall underestimations of precipitation (regression slopes of 0.3-0.7, $R^2 \ge 0.46$). (2) The two NDVI products inferred different vegetation phenology characteristics. (3) Increased mean pre-season temperature significantly influenced the advance of SOS and delay of EOS. The precipitation influence was weaker, but delayed SOS corresponding to increased preseason precipitation at most sites can be related to later snow melting. (4) Decreased

catchment streamflow over the last 15 years could be related to the advance in SOS and extension of growing seasons. Greater streamflow reductions in the cold sites than the warm ones imply stronger climate warming impacts on vegetation and hydrology in colder northerly environments. The methods used in this study have potential for better understanding interactions between vegetation, climate and hydrology in observationscarce regions.

Key words: vegetation phenology; climate; hydrology; temperature; precipitation; streamflow

1 Introduction

Climate change, particularly warming induced by increasing atmospheric greenhouse gases, has been suggested as the main cause of recent alterations in vegetation phenology (Penuelas, 2001; Zhou et al., 2001; Estrella and Menzel, 2006). Climatedriven variations in phenology can have major impacts on the functioning of terrestrial ecosystems by altering carbon, water and energy balances (Ziska et al., 2011; Piao et al., 2015). Exploring the relationships between vegetation phenology and climate variability can improve our understanding of how ecosystems will react to climate change and affect hydrological processes governing the water balance. This will improve our understanding of the likely effects of future climate change on phenology and improve conceptualisation of the role of vegetation in global carbon and water cycle modelling (Mendoza et al., 2017; Hwang et al., 2018).

The high latitudes of the Northern Hemisphere are particularly sensitive to climate change (IPCC, 2014). The hydrological implications can be especially profound, as slight changes in air temperature can alter the form, timing, and magnitude of precipitation (Brown and Mote, 2009), snowmelt and the consequent influence on streamflow and water storage dynamics (Barnett et al., 2005). Such hydrological effects have the potential to change further the structure and function of terrestrial and aquatic ecosystems in the long term, which may include feedbacks on plant water use strategies (Kruitbos et al., 2012; Richardson et al., 2013; Wang et al., 2018).

A number of studies have demonstrated that the onset dates of vegetation green-up and dormancy (here used interchangeably with start and end of growing season, respectively, and denoted as SOS and EOS) in the high-latitude North have advanced and delayed, respectively (Lucht et al., 2002; Garonna et al., 2016). However, due to differences in ecosystem composition, geographic location and study period, a wide range of growing season changes has been reported (Wu and Liu, 2013; Jeong et al., 2011; Tao et al., 2017). The detected changes in growing seasons have been mostly related to climatic drivers such as air temperature (Ta), precipitation (P) and atmospheric CO₂ concentration (Estrella and Menzel, 2006; Forkel et al., 2015; Piao et al., 2015). These studies indicate that seasonal vegetation cycles are regulated by multiple, often interacting, factors whose relative importance is likely to be region-specific (Buitenwerf et al., 2015). For example, studies have variously shown strong

temperature controls on leaf-out, but not on senescence, in Europe (Menzel et al., 2006), contrasting roles of increasing temperature and elevated CO₂ concentration on leaf-out and senescence in a North American grassland (Reyes-Fox et al., 2014), and the cocontrol of temperature, elevation, snow cover and sunshine hours on leaf green-up and dormancy on the Tibetan Plateau (Piao et al., 2011; Wang et al., 2013, 2015).

Changes in growing season duration (GSD) induced by these factors have tended to enhance vegetation growth (Ivits et al., 2014), which has been reported positively affecting annual carbon exchange (indicated by e.g., increased gross primary productivity) (Keeling et al., 1996; Myneni et al., 1997; Piao et al., 2007). Extended growing seasons have also increased terrestrial evapotranspiration (ET) at several northern sites (White et al., 1999; Hwang et al., 2014; Kim et al., 2018). Compared to the causal mechanisms, such ecohydrological implications of growing season changes are relatively under-explored. In particular, the effects of changes in vegetation phenology timing on catchment water partitioning, especially the relative importance of "green" water fluxes in ET and "blue" water fluxes to groundwater recharge and runoff, are not well documented. This is due mainly to the lack of concurrent long-term field observations of both vegetation phenology and hydrometeorology, which are crucial for empirical understanding of catchment processes and validation of modelled or remotely sensed data (Burt and McDonnell, 2015; Tetzlaff et al., 2017).

Data assimilation systems in hydroclimatology provide continuous estimations of meteorological and hydrological components globally with increasing accuracy and finer temporal resolution, although the spatial resolution remains relatively coarse, such as the 25-100 km grid size of the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004). Nevertheless, such assimilated data may help bridge investigations of climate-vegetation-hydrology interactions from the regional to local scales. Similar to assimilation data, remote sensing data also have extensive spatial coverage and temporal dynamics for the observed variables, and are less constrained by high costs and logistical difficulties of data acquisition in remote areas; nevertheless, they need local calibrations (e.g., Menzel, 2000; Schwartz and Reiter, 2000). For vegetation phenology studies, two NDVI (Normalized Difference Vegetation Index) products are commonly used: one is derived from the AVHRR (Advanced Very High Resolution Radiometer) provided by the GIMMS group (Global Inventory Monitoring and Modeling Studies) at ~8 km resolution (Tucker et al., 2005), and the other from the MODIS (Moderate Resolution Imaging Spectroradiometer) at 0.25-5.6 km resolution (Didan, 2015).

In this study, we assessed the implications of phenological changes for catchment hydrology. To do this, we combined satellite NDVI data, assimilated and observed hydrometeorological data in six northern high-latitude catchments, aiming to investigate the climate-vegetation-hydrology interactions. Specifically, we addressed

the following questions: (1) How has vegetation phenology changed as inferred by remote sensing NDVI data? (2) How do antecedent climatic conditions influence the changes in vegetation phenology? And (3) what are the hydrologic implications of these phenology changes for streamflow variations in the growing season?

2 Data and methods

2.1 The six experimental catchments

<Figure 1 Here>

The six headwater catchments (Figure 1a) are the Bruntland Burn in Scotland, Krycklan in Sweden, Dorset, Moss Creek and Wolf Creek in Canada, and Dry Creek in the United States. These catchments are located in natural areas with very limited human activities. The comparison of mean annual temperature (MAT) and mean annual precipitation (MAP) across the catchments are shown in Figure 1b. Details of hydroclimates, vegetation, soils and geology in these catchments can be found in Tetzlaff et al., (2014), Laudon et al., (2013), Buttle and Eimers (2009), Spence et al., (2009), McCartney et al., (2006), and McNamara et al. (2017). A summary and comparison of hydrology among these catchments was given in Carey et al., (2010) and Tetzlaff et al., (2015).

In brief, along a temperature gradient, Moss Creek is the coldest and driest catchment, with around 42% of MAP falling as snow. The predominant vegetation is open black spruce (*Picea mariana*) forest that occupies 25% of the basin. Wolf Creek is the second

coldest site and has the second lowest precipitation. 40% of MAP falls as snowfall. Vegetation consists of willow (Salix) and birch (Betula) shrubs at lower elevations and tundra at higher elevation. Krycklan, the third coldest, is the most easterly and northerly site, with 40% of MAP as snow. Forest cover consists largely of Scots pine (Pinus sylvertris) and Norway spruce (Picea abies). Dorset and Bruntland Burn are mild in temperature with the highest amount of precipitation. In Dorset, approximately 33% of MAP falls as snow, while Bruntland Burn has only ~5% of MAP as snow. Vegetation consists of mixed deciduous-conifer forest of primarily white pine (Pinus strobus), eastern hemlock (Tsuga Canadensis), red oak (Quercus rubra), and red maple (Acer rubrum) on the drier uplands and white cedar (Thuja occidentalis) in low-lying wetland areas (Watmough and Dillon, 2001). Vegetation cover is characterized by heather (Calluna vulgaris) shrubs on steeper slopes and Sphagnum spp and Molina caeruleadominated blanket bog in riparian areas. Dry Creek is the warmest catchment. Most precipitation falls in the winter months as snow in the uplands and rain in the lowlands. This catchment was selected to include a snow-influenced area with higher energy inputs in contrast to the other catchments of low energy. Vegetation is predominantly sagebrush (Artemisia tridentata) and a variety of riparian vegetation at lower elevations. Higher elevations contain forested areas composed mostly of Douglas Fir (Pseudotsuga menziesii) and Ponderosa pine (Pinus ponderosa).

2.2 Data

Details of the data used in this study are given in Table 1. Onset dates of growing season were derived from normalized difference vegetation index (NDVI) data from GIMMS (Global Inventory Monitoring and Modeling Studies) and MODIS (Moderate Resolution Imaging Spectroradiometer). As NDVI is calculated from surface reflectance (Huete et al., 2002) which is a result of the integrated surface conditions such as vegetation types and density, the spatial coverage of NDVI pixels is therefore important for interpretation of surface phenology. Meteorological data including air temperature (Ta) and precipitation (P) were obtained from two sources: the GLDAS (Global Land Data Assimilation System) assimilation system with the Noah land surface model (Rodell et al., 2004), and direct measurements from automatic weather stations within the catchments. Streamflow was measured at the outlet of each catchment to quantify the integrated response of catchment hydrology to climate and vegetation changes. To match the spatial resolution of GLDAS assimilation data for analysis of climatic impacts on vegetation phenology, we aggregated the 8-km GIMMS-NDVI to 25 km.

<Table 1 Here>

2.3 Methods

To ensure the full coverage of the catchments, we extracted the pixels of GLDAS and NDVI data that intersect with and are located in the catchment boundaries. Pixels dominated by urban, cropland, water and snow were excluded in the analysis due to the lack of distinct seasonality in greenness (Yang et al., 2015). To assist the filtering, land cover types were obtained from MODIS MCD12Q1 in 2013 which is based on the International Geosphere-Biosphere Programme classification method (Friedl et al., 2002), with the assumption that the land cover types do not change significantly with time due to limited human activities.

We modified the method in Piao et al., (2006) to determine SOS and EOS using NDVI series. First, average NDVI at each 16-day time step over all years was calculated and fitted by a 6-degree polynomial function to reconstruct the daily NDVI series (Yang et al., 2015). Derivatives of the fitted curve were then calculated to pinpoint the steepest rates of change on each side of the curve. The NDVI values at these two changing points were taken as the thresholds for the start and end of a growing season. Second, onset dates were estimated by applying the threshold values on reconstructed daily NDVI curves for each year. This was done for each catchment to obtain SOS and EOS for 1982-2015 using GIMMS-NDVI, and for 2001-2016 using MODIS-NDVI. Linear regression was then applied to estimate the trend of SOS and EOS change over years;

t-test *p* values were given to indicate statistical significance. Temporal variability of estimated SOS and EOS was indicated by standard deviation of the results over all years.

To test the performance of regional assimilation data for local scale studies, we compared the monthly 25 km GLDAS estimates of Ta and P with measurements in each catchment. Linear regression slope (k), coefficient of determination (R^2) and root mean square error (RMSE) were used to test the goodness of fit. Furthermore, to investigate the climatic effects on vegetation change, we examined relationships between preseason mean temperature, precipitation and vegetation onset dates using partial correlation analysis (Piao et al., 2015), which can eliminate effects of alternative factors while examining one potential control. Previous studies have shown that climate conditions in the 1-2 month period prior to onset are most important in influencing vegetation phenology (Fitter and Fitter, 2002; Piao et al., 2006). Therefore, we only tested the relationships for 0 to 3 months prior to the onset month of each year inferred by NDVI data. The partial correlation coefficient (r) was used to indicate the degree of influence, i.e. a higher r infers a likely stronger influence of climate on vegetation phenology

Lastly, we tested relationships between SOS, EOS (and thus growing season duration, GSD) and growing season streamflow for each catchment, to investigate potential vegetation impacts on catchment hydrology. SOS and EOS in this test were obtained

from the MODIS-NDVI data only, because the streamflow was measured directly at the catchment scale. Linear regression slope, R^2 and *p*-values were given to describe and evaluate the impacts. Streamflow is directly affected by precipitation in addition to growing season duration; therefore, to differentiate the effects of both factors on streamflow, we applied multiple linear regression (equation 1) after standardizing streamflow, precipitation and growing season duration. To standardize the variables the mean values were subtracted first and then divided by standard deviations. In this way, the regression coefficients can be directly used to infer the relative degree of influence of P and GSD on streamflow.

$$sQ = c_0 + c_p \times sP + c_g \times sGSD \tag{1}$$

where sQ, sP and sGSD are standardized streamflow, precipitation and growing season duration; c_0 , c_p and c_g are regression coefficients. c_0 is zeros when using standardized variables.

3 Results

3.1 Growing season changes based on NDVI datasets

<Figure 2 Here>

Onset dates inferred by the NDVI datasets differed in general as did several of the linear trend directions (Figure 2), with the longer GIMMS time series showing relatively

higher levels of statistical significance. The Krycklan, Dorset and Bruntland Burn sites all showed advanced SOS and delayed EOS based on GIMMS-NDVI (1982-2015), while the other sites showed delayed SOS and advanced EOS. In contrast, all sites showed advanced SOS and delayed EOS based on MODIS-NDVI (2001-2016), except for advanced EOS in Bruntland Burn and Wolf Creek. Meanwhile, the magnitudes of SOS and EOS trends were variable. For example, SOS advanced by 0.5 days/year inferred by GIMMS-NDVI compared to 1.1 days/year by MODIS-NDVI at Bruntland Burn; the SOS advance rates for Krycklan were 0.5 and 0.2 days/year, and for Dorset were 0.3 and 0.1 days/year, respectively.

The temporal variability in SOS and EOS reflected by the standard deviation was smaller at the coarse resolution relative to the fine resolution. Linear trends of onset dates were overall more statistically significant at 25 km resolution where datasets were longer. Interestingly, SOS inferred by fine resolution NDVI occurred earlier at almost all sites while EOS occurred later (thus showing a longer growing seasons), compared to results from the coarse NDVI. Although values of SOS from two NDVI datasets in the most recent 15 years were different, the temporal dynamics were similar at Krycklan, Moss Creek and Dorset, indicated by high correlation coefficients (0.63, 0.72, and 0.80, respectively). Dynamics of EOS in the same period were similar only at Krycklan with a correlation coefficient of 0.45. At the other sites, the overall temporal correlations of SOS and EOS were weak even if there was similarity among a few years.

3.2 Comparison of assimilated and observed climate data

<Figure 3 Here>

To assist the analysis of climatic influences on vegetation phenology and to test the suitability of regional climate data for local catchment studies, we compared the assimilated temperature and precipitation from GLDAS to catchment observations at each site from 2000 onwards (Figure 3). Monthly temperature from GLDAS was in good agreement with measurements in all catchments ($k\approx 1.0$, $R^2\approx 1.0$), although there was slight overestimation at Wolf Creek (k=1.2) and underestimation at Bruntland Burn (k=0.9). Precipitation data from both assimilation system and field measurements were also consistent in temporal dynamics (R^2 ranges from 0.46 to 0.66); however, consistent underestimations by GLDAS were evident at all sites (especially Wolf Creek and Moss Creek) with the regression slope ranging from 0.3 at Wolf Creek to 0.7 at Dry Creek. Underestimation largely resulted from the mismatch in summer months.

3.3 Climatic influence on vegetation growing seasons

<Figure 4 Here>

Based on the temperature and precipitation from GLDAS and field observations and vegetation phenology results from the two NDVI datasets, we calculated the partial correlation coefficient between mean pre-season Ta and cumulative P and SOS, EOS in Figure 4 to evaluate the climatic influences on growing season changes. The pre-season temperature imposed a stronger influence on growing seasons than precipitation,

indicated by generally higher correlation coefficients between SOS, EOS and Ta than between SOS, EOS and P. Negative correlation coefficients between SOS and Ta, and positive correlation coefficients between EOS and Ta imply that higher temperature in preceding months caused advanced SOS and delayed EOS, respectively. Nevertheless, pre-season P at Wolf Creek and Dorset also seem to be strongly correlated with phenology. And, the influence of Ta on phenology was mostly strongly evident when based on the MODIS-NDVI and local meteorological measurements compared to the GIMMS-NDVI and GLDAS data.

The importance of mean pre-season Ta in affecting the growing season varies among sites. Generally, mean Ta over the 1-3 months prior to onset played a significant role in advancing vegetation green-up. Thus, a warm winter leads to an early start of growing season. Temperature in the onset month or 1 month earlier influenced the end of growing season the most. The influence of pre-season P on SOS and EOS was weaker than Ta, although more precipitation in preceding months led to delayed SOS almost in all catchments, while higher pre-season precipitation was correlated with earlier EOS at Wolf Creek and Krycklan.

3.4 Impacts of vegetation change on growing season streamflow

<Figure 5 Here>

Climate-driven changes in vegetation growth have the potential to trigger hydrologic responses. As streamflow (Q) is an integrated residual of other catchment hydrologic fluxes, and easiest to measure, we examined the relationships (Figure 5) between catchment streamflow during the growing season (from April to October) and the growing season changes inferred by MODIS-NDVI. Decreased streamflow during April-October was coincident with advanced SOS at all sites. It is notable that the relationships were only statistically significant at the two driest sites: Dry Creek and Wolf Creek (p < 0.05). The decrease in streamflow was more strongly related to an earlier start, rather than a later end, of the growing season at all catchments, showing larger regression slopes between streamflow and SOS than between streamflow and EOS. As expected, streamflow in all catchments decreased with prolonged growing seasons. The rate of streamflow reduction with increasing GSD was higher at Moss Creek, Wolf Creek, and Krycklan (~3.0 mm/day) compared to the other three catchments. Interestingly, we also found that the reduction in catchment streamflow with extended growing seasons generally became smaller along the increasing gradient of temperature from coldest Moss Creek to warmest Dry Creek (decreasing slopes in the 3^{rd} column of Figure 5).

Of course, independent of any vegetation changes, growing season streamflow is also likely to be strongly related to precipitation. Therefore, linear regression analysis was carried out between precipitation and streamflow at a monthly scale. Results show that strong correlations occur at Wolf Creek, Bruntland Burn and Dry Creek with R^2 values of 0.45, 0.80 and 0.53, respectively (p<0.05). Regression slopes (0.5, 0.4 and 0.3, respectively) indicate that these catchments have higher mean monthly runoff coefficients compared to other catchments. In addition to the above regression analysis, we also performed multiple linear regression analysis using standardized variables to differentiate the influence of precipitation and vegetation growing season on streamflow. Standardized coefficients are given in Table 2.

<Table 2 Here>

The c_g coefficients at Moss Creek and Wolf Creek are larger than c_p , which implies that vegetation growing season change affects streamflow more strongly than precipitation at these two sites. In contrast, the effect of precipitation was much stronger than vegetation changes at the other sites, especially Krycklan, Bruntland Burn and Dry Creek. The effects of precipitation and growing season duration were similar at Dorset. Therefore, combining the results of relationships between GSD and Q and between P and Q as well as the coefficients in Table 2, it seems that at the colder sites the

vegetation growing season duration has a greater influence on streamflow, whilst at the warmer sites the effects of precipitation on streamflow are stronger.

4 Discussion

4.1 Vegetation phenology in response to climatic factors

Vegetation phenology is estimated from remote sensing NDVI data which are based on surface reflectance (Huete et al., 2002). The reflectance of each grid cell represents the combined information of vegetation species composition, distribution and growth status (Vermote, 2015). Therefore, the spatial resolution of NDVI data matters for the actual vegetation information derived from a pixel. It is not surprising then to have different phenology onset dates obtained from the two NDVI datasets. The growing season durations inferred by MODIS-NDVI are more consistent with the empirical knowledge in the catchments linked to the dominant vegetation types: longest growing season at Bruntland Burn, followed by Dorset, and shortest at Dry Creek.

Vegetation phenology is affected by climatic conditions. Warmer winter temperature correlated with earlier SOS, whereas warmer summer temperatures correlated with delayed EOS. The same temperature controls in vegetation growing seasons have been consistently reported elsewhere (Tanino et al., 2010; Richardson et al., 2013; Zhang et al., 2013). The influence of temperature on SOS is stronger than on EOS, similar to some studies in northern regions (Menzel et al., 2006; Güsewell et al., 2017).

Furthermore, we observe that the temperature control on phenology is generally stronger at the colder sites (Figure 4). The influence of precipitation on vegetation change is expected to be stronger in dry areas than humid areas (Ramos et al., 2015; Tao et al., 2017), for example, a stronger influence of precipitation than that of temperature was discovered in water-limited biomes such as the arid desert (Yang et al., 2015) and dry steppe (Zhu and Meng, 2014). In this study, precipitation influence was not evident at most of these northern catchments; however, the pre-season precipitation influence on SOS is positive at the cold sites (Wolf Creek, Krycklan and Dorset), indicating that more winter precipitation is correlated with a delayed start of growing season. As radiation is the primary controlling factor for vegetation growth in the northern high latitudes (Wang et al., 2017). This phenomenon is likely to be attributable to low radiation available for vegetation growth due to increased surface albedo after winter precipitation occurs, which is mostly snowfall in almost all sites except Bruntland Burn. In addition, the snowpack is usually thicker with increased winter precipitation at the colder sites and would need a longer time to melt in spring, postponing the timing when the threshold temperature that triggers vegetation growth is reached (Fu et al., 2015; Piao et al., 2015). In summary, based on the results from this and previous studies, the responses of vegetation phenology to climate variability appear to be regionally specific, and the controlling mechanisms, and their interactions, do not seem consistent across sites.

4.2 Using regionally-assimilated data in catchment ecohydrology

Direct observations are fundamental for understanding atmospheric and hydrologic processes and their interactions. In remote, sparsely monitored areas, substitute data may be obtained from assimilation systems such as GLDAS (as used in this study) and others such as ERA-Interim by ECMWF (Berrisford et al., 2011). However, assimilated data need to be validated before they can be used for quantitative purposes. In this study, GLDAS 25 km assimilated monthly temperature shows very good agreement with measurements at all six northern catchments. The good performance of GLDAS temperature assimilation has also been shown by others in different regions (e.g. Wang et al., 2011; Zhou et al., 2013; Ji et al., 2015), implying small variability of temperature across spatial scales. Meanwhile, the assimilated precipitation underestimates local measurements significantly. Underestimation is most pronounced during summer periods, particularly at the two coldest sites Moss Creek and Wolf Creek. High intensity rain events seem poorly captured by the assimilation system. In addition, the deteriorated performance of GLDAS for precipitation assimilation compared to temperature may reflect the greater spatial variability of precipitation (Tokay et al., 2014; Cristiano et al., 2017). The mismatch of summer rainfall has also been reported by other comparative studies, such as in Qi et al., (2016) over an east China basin. Underestimation of precipitation by GLDAS was also observed at six sites in the United States where winter precipitation was the main factor attributable to the underestimation

(Broxton et al., 2016). Inaccurate precipitation inputs for hydrologic models would result in large uncertainty in streamflow simulations (Zaitchik et al., 2010; Liu et al., 2017), especially for summer high flows (Cristiano et al., 2017). This stresses the need for assimilation model improvement towards better hydrological insight and understanding.

4.3 The hydrologic consequences of vegetation phenology change

In terms of vegetation impacts on catchment hydrology, previous studies have shown that a prolonged growing season can enhance plant growth and thus increase transpiration (Berninger, 1997; Hwang et al., 2014). In these low-energy northern catchments, soil evaporation is limited, and transpiration contributes most of the total evapotranspiration (Sprenger et al., 2018; Wang et al., 2018). Increases in transpiration can result in a decline in streamflow (Deutscher et al., 2016; Kim et al., 2018). Although the response time of streams to ET losses is often unclear, here we simply looked at the growing season as first indicator in the study catchments. Streamflow decline in response to extended growing season was observed in this study, though only statistically significant at two sites despite being consistent across the catchments. The impact of advanced SOS on reduced streamflow is more marked than that of delayed EOS. This could be a result of both transpiration and water storage change, because transpiration is usually higher at the early stage of growing season when water storage and energy input are both at an optimal condition for plant growth (Wang et al., 2016).

In contrast,, at the late stage of growing season transpiration rates can decrease due mainly to the decline in soil water storage (Manzoni et al., 2014). The delayed EOS showed varying impacts on streamflow across sites: streamflow at Moss Creek, Wolf Creek and Bruntland Burn decreased with delayed EOS, whereas an opposite relationship was apparent at the other catchments. This supports the non-universal relationships between vegetation changes and water fluxes proposed by Richardson et al. (2010, 2013).

Precipitation is also closely related to streamflow (Tetzlaff and Uhlenbrook, 2005; Penna et al., 2015), and we found statistically significant relationships at Wolf Creek, Bruntland Burn and Dry Creek. Moreover, the standardized multiple linear regression analysis, which we used to compare the influences of precipitation and growing season duration on streamflow, shows that GSD exerts a stronger impact than precipitation at the two coldest sites (Moss Creek and Wolf Creek) whereas at other catchments the opposite relationship holds. Previous hydrologic studies in the catchments showed that the seasonality of precipitation, storage (both in soil and snowpack) and topography affect streamflow generation. The P-Q relationships are usually strong in catchments with high precipitation inputs or steep topography (Soulsby et al., 2009). For catchments with significant snow storage, a spring freshet will clearly reduce the correlation between monthly P and Q (Carey et al., 2010). In addition to these factors affecting streamflow, taking the advantage of long-term observations in the catchments,

here we found indications that the rate of reduction of streamflow with extended growing season decreased from cold to warm sites (3rd column in Figure 5). This observation tentatively implies that the more marked vegetation change induced by global warming has imposed a stronger alteration in catchment hydrology in the cold rather than warm areas. This stresses the importance of efforts to identify and tackle potential challenges to water resources due to future climate change, particularly in summers when the water consumption is usually high.

5 Conclusion

This study provides an analysis of climatic controls on vegetation phenology and the potential hydrologic responses to vegetation change in six northern high-latitude catchments. The major findings and conclusions are summarized below:

(1) Estimates of vegetation growing seasons differ with remote sensing vegetation index data used.

(2) Pre-season temperature exhibited strong controls on vegetation phenology, whereas the influence of precipitation was weaker, although at some sites delayed start of the growing season corresponded to increased winter precipitation which may be related to later snow melting.

(3) A decrease in streamflow corresponded to advanced SOS and extended growing seasons, and the rates of streamflow reduction decreased along an increasing temperature gradient. This pattern suggests that warming-induced vegetation change has more discernable impacts on catchment hydrology in colder high latitudes in terms of changes in water fluxes.

(4) In addition, the application of assimilated climate data demonstrates the usefulness of large-scale data for local scale ecohydrological studies, especially temperature, whilst precipitation data may need closer evaluation.

This study shows the potential for investigating climate, vegetation and hydrology interactions in sparsely monitored regions by fusion of remote sensing and assimilation data with limited empirical observations. It also underlines that the northern high latitudes are sensitive to climate change impacts, reflected by the changes in vegetation phenology and catchment hydrology. The findings bring us forward regarding the study of impacts of vegetation on catchment hydrology and provides a basis for future integration of data sources.

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Table 1 A summary of data used in this study, including remote sensing vegetation index (NDVI), assimilated (temperature and precipitation) and measured data (temperature, precipitation, and streamflow).

Variables	NI	IVI	Tempera precipi	Streamflow	
Data sources	GIMMS- NDVI3g v1	MODIS MOD13A1 v006	GLDAS-Noah v2.0 & v2.1	Observations in each catchment	Observations in each catchment
Spatial resolution	~8 km	0.5 km	~25 km	R	-
Temporal resolution	Biweekly	16-day	Monthly	Sub-daily	Sub-daily
Temporal coverage	1982-2015	2001-2016	1982-2015	2000-2016	2000-2016

Table 2 Coefficients of multiple linear regression based on standardized streamflow, precipitation (in April-October) and growing season duration in equation (1). Coefficient c_0 for all site is zero, c_p is coefficient for precipitation, and c_g is coefficient for growing season duration.

coefficient	Moss	Wolf	Krycklan	Dorset	Bruntland	Dry
	Creek	Creek			Burn	Creek
Ср	0.28	0.13	0.81	0.45	0.79	0.68
Çg	-0.67	-0.56	-0.18	-0.30	-0.09	-0.35
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Figure 1 (1) locations of the studied catchments; (b) characterization of mean annual hydroclimates across the catchments based on field measurements. The centers of the lines are the mean annual values of the relevant variables. The lines represent annual values in all the years, showing also the difference from the mean annual values.



Figure 2 Start and end of growing seasons (SOS & EOS) inferred by NDVI for the six catchments. In the legend, 25 km refers to results from GIMMS NDVI in blue; 0.5 km refers to results from MODIS NDVI in red. Linear regression slope is in unit of days per year; positive means delayed, and negative means advanced. Bars on the curves are standard deviations to show temporal variability of SOS and EOS.



Figure 3 Comparison of temperature (Ta) and precipitation (P) between GLDAS assimilation data and field measurements for the six catchments. Slopes (k) less than 1 means GLDAS underestimates observations. *RMSE* is root mean square error, and unit is °C for Ta and mm for P. Note the data availability across catchments is different so the time in horizontal axis is not necessarily continuous or the same.



Figure 4 Partial correlation coefficients between start and end of growing season (SOS, EOS) and pre-season mean temperature (Ta) and pre-season accumulated precipitation (P) during 1982-2015 based on 25 km data, and during 2001-2015 based on 0.5 km data. preS₀ refers to the onset month; preS₁₋₃ refer to a period from preceding 1-3 months to the onset months. For example, if SOS is in April, preS₀ refers to April, preS₁ refers to March and April.



Figure 5 Relationship between growing season (April-October) streamflow and start, end and duration of growing seasons (SOS, EOS, and GSD) at the six catchments during 2001-2016. Plots are arranged in an increasing order of annual mean temperature from top to bottom (i.e. cold to warm sites). SOS and EOS are based on MODIS NDVI. k (mm/day) in the plots is linear regression slope, p indicates statistical significance level.



Highlights

- We examined the climate-vegetation-hydrology interactions in northern catchments
- Regional climate assimilation data are useful for local ecohydrological studies
- Pre-season temperature had stronger influence on phenology than precipitation
- Streamflow decline corresponded to advanced green-up and extended growing seasons
- Global warming appears to be affecting ecohydrology strongest at colder sites

A CLARANCE