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Correlation Analysis of Mackenzie River Discharge and NDVI Relationship

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Abstract. This study, based on the analyses of long-term discharge and Normalized Difference Vegetation Index (NDVI) data, revealed a strong seasonal consistency between NDVI and discharge over the Mackenzie River Basin in Canada. The flow–NDVI association is particularly strong in the early growing season (May to the 1st half of June). During this period, discharge rapidly rises and reaches the peak, whereas NDVI increases around the 1st half of May and reaches the maximum at the 2nd half of July. In the mid- and late summer, both discharge and NDVI decline gradually. Correlation analyses identify 2 sensitive periods, i.e., May to June and the 2nd half of July to the 1st half of September, when NDVI significantly responds to discharge variations. In the first period, the half-month NDVI highly correlates to the 1st half of May discharge, indicating that spring flow has a strong influence on vegetation growth in the early growing season. Spatially, almost all of the basin shows a high correlation, except Mackenzie and the Rocky Mountains and the region near the eastern edge of the basin. For the 2nd period, from the 2nd half of July to the 1st half of September, the NDVI relates closely to discharge with lags of 0–5 half-months. Trends analyses suggest river discharge increased during 1982 to 2006 in most seasons except summer. The NDVI trends during the growing season (May to September) clearly correspond to discharge changes. Examination of extreme flow years and corresponding NDVI conditions over the basin also reveal that a lower runoff was associated with a lower basin NDVI with an earlier maximum, whereas the higher flow was linked with a higher NDVI and a longer growing season.

Résumé. Cette étude, basée sur les analyses de débit à long terme et des données de l'indice de végétation par différence normalisée «Normalized Difference Vegetation Index» (NDVI) a indiqué une forte cohérence saisonnière entre NDVI et le débit sur le bassin du fleuve Mackenzie au Canada. L'association entre le débit et NDVI est particulièrement forte en début de saison de croissance (mai à la mi-juin). Pendant cette période, le débit augmente rapidement et atteint son maximum, tandis que NDVI augmente autour de la première moitié de mai et atteint le maximum à la 2e moitié de juillet. Au milieu et à la fin de l'été, le débit et NDVI diminuent progressivement. Les analyses de corrélation identifient 2 périodes sensibles, à savoir, mai à juin et la 2e moitié de juillet à la 1er moitié de septembre, tandis que NDVI répond de manière significative aux variations du débit. Dans la 1er période, NDVI intégré sur un demi-mois est fortement corrélé à la 1er moitié du débit de mai, ce qui indique que l'écoulement printanier a une forte influence sur la croissance de la végétation en début de saison de croissance. Spatialement, la quasi-totalité du bassin montre une forte corrélation, à l'exception des monts Mackenzie et les montagnes Rocheuses et la région près de la bordure est du bassin. Pour la 2e période de la 2e moitié de juillet à la 1er moitié de septembre, NDVI est étroitement lié au débit avec un décalage de 0 à 5 demi-mois. Les analyses des tendances suggèrent que le débit de la rivière a augmenté entre 1982 et 2006 pour la plupart des saisons sauf en été. Les tendances NDVI pendant la saison de croissance (de mai à septembre) correspondent clairement aux changements de débit. L'examen des années avec un débit extrême et des conditions NDVI correspondantes sur le bassin révèle également qu'un ruissellement plus faible est associé à un NDVI de bassin inférieur avec un maximum plus tôt, alors que le débit plus élevé a été lié à un NDVI plus élevé et une saison de croissance plus longue.

INTRODUCTION

Climate in the northern regions has experienced significant changes over the past decades. These changes affect the northern environment ($\geq 45°$ N), including ecosystem, hydrology, and permafrost (Saito et al. 2012). Vegetation processes in the northern regions are a clear indication of ecosystem function. Many studies report ecosystem changes associated with strong climate warming in the northern regions, such as earlier and longer growing seasons (Kim et al. 2012; Nemani et al. 2003), greening of the landscape (Beck and Goetz 2011; Hudson and

Henry 2009; Bunn and Goetz 2006), increases in productivity (Zhang et al. 2008), northward shift in vegetation biomes (Lucht et al. 2006), and tundra shrub expansion (McManus et al. 2012; Tape et al. 2012). Water, soil condition, and energy are the main factors for vegetation distribution and functions over the large regions. Vegetation growth is affected by meteorological and soil variables and the spatial distribution of these variables across the landscape. Some studies suggest that vegetation growth in the northern regions is mainly constrained by seasonal temperatures and the exchange of heat and moisture (Fraser et al. 2011; Qian et al. 2010; Friedlingstein et al. 2006; Nemani et al. 2003). Recent investigations indicate that widespread drought and wildfire enhanced by climate warming could also have led to frequent tree mortality and declines in the boreal productivity over the northern regions (Girardin et al. 2014).

The Normalized Difference Vegetation Index (NDVI) has been widely used to investigate vegetation changes and their relationship with regional climate. Several studies reveal an increasing NDVI trend over the northern regions, including Canada. Pouliot et al. (2009) find that 22% of the vegetated areas in Canada have a positive NDVI trend during the last 20–30 years; of these, 40% were in northern ecozones. In the southern regions of Canada, the NDVI changes were less consistent and relatively weak. Local assessment of potential causes of the NDVI trends show a stronger influence on climate in the north compared to that in the south. Human activities also impact vegetation activities and their changes. The positive NDVI trends in southern regions of Canada were influenced mostly by land cover change (Olthof and Latifovic 2007). Over the cold regions, NDVI has a strong relationship with air temperature and precipitation in alpine and subalpine plains/grasslands in the Qinghai–Tibet Plateau (Zhong et al. 2010). A good relationship has been found between NDVI and rainfall in the meadows and grasslands with medium vegetation cover in the central and eastern Qinghai–Tibet Plateau (Ding et al. 2007). In northern regions, such as Canada, the principal factor for the vegetation process seems to be energy, although soil water is also important (Bi et al. 2013; He et al. 2012; Wang et al. 2011; Bhatt et al. 2010). Over many regions in Canada, soil water supply is gradually reduced from spring to summer season. Snowmelt in spring recharges soil layers and ground water storage, thus supporting plant growth over many regions in Canada (Bi et al. 2013; Kim and Wang 2007).

Kim et al. (2014) recently analyzed new global satellite data of daily landscape freeze–thaw (FT) from 1979 to 2010 and evaluated the ecological significance of these changes against the NDVI anomalies over the broad northern ($\geq 45°$ N) regions. They pointed out that cold temperature constraints to northern growing seasons are relaxing, whereas potential benefits for productivity and carbon sink activity become more dependent on the terrestrial water balance and supply of plant-available moisture necessary to meet additional water use demands under a warming climate. Other studies also clearly demonstrate the increasing importance of water availability to the northern

ecosystem, in a warming climate (Bi et al. 2013; Bertoldi et al. 2011; Olthof and Latifovic 2007). It is important to point out that river discharge is the direct measure of water storage and availability over large regions and northern watersheds. In the high latitudes, spring snowmelt runoff and its peak reflect the amount of winter snow accumulation and the melt process (Yang et al. 2002; Yang, Shi, et al. 2014), summer discharge and high floods respond to heavy rainfall activities, and fall–winter base flows indicate basin storage capacity and a recession process. River flows integrate basin processes, including surface water mobility, recharge of soil moisture, and subsurface storage variation over space and time. River discharge has been systematically observed in the northern basins, but it is very difficult to measure soil moisture and recharge rate over large regions. Climate variables have been often used to infer soil moisture conditions. For instance, the climatic moisture index (CMI), i.e., mean annual precipitation (P) minus mean annual potential evapotranspiration (PET), has been defined and related with vegetation and forest processes (Hogg 1994, 1997), including the impacts of regional droughts and climate change on forest growth and dieback. It is important to note that, in terms of basin water balance, this index (P−PET = Runoff + storage change) reflects river runoff and basin storage or, in other words, basin water availability. Over most northern basins, river runoff is much higher in magnitude than the storage term and its change. Many studies report remarkable changes in the northern hydrology systems, such as increases of Eurasian Arctic river discharge (McClell et al. 2006; Peterson et al. 2002), discharge increases in winter and decreases in summer for the Yenisei, Lena, and Ob watersheds in Siberia (Yang, Ye, and Kane 2004; Yang, Ye, and Shiklomanov 2004; Ye et al. 2003), earlier melt of snow cover (Fretwell et al. 2010; Yang et al. 2005; Myneni et al. 1995) and river ice breakup (Prowse et al. 2010; Bonsal et al. 2006), and shift of peak flows in the spring season for the Yukon and Mackenzie rivers (Yang, Shi, et al. 2014; Ge et al. 2012; Yang et al. 2005). These changes in streamflow hydrology features are caused by climate variations and human impacts (Yang, Ye, and Kane 2004; Yang, Ye, and Shiklomanov 2004; Ye et al. 2003).

Our knowledge of vegetation-hydrology linkage over the broader northern regions is incomplete. Long-term discharge and NDVI records are available on a global scale. Most NDVI analyses have been done on regional scales, however, there is little effort to systematically examine their interactions over the large northern rivers with significant past and ongoing environment changes. It is clear that both hydrology and ecology are changing in the high latitudes. But there are many major questions for ecohydrology research; for instance, what are the characteristics of basin hydrology, ecology, and their changes? What is the impact of basin hydrology change to ecosystem function? Is there (in)consistency in river flow and vegetation trends over the northern basins? In order to fill these knowledge gaps, basin-scale analyses of ecohydrology are necessary. This study compiles and analyzes long-term discharge and NDVI data over one of the largest rivers in North America—the
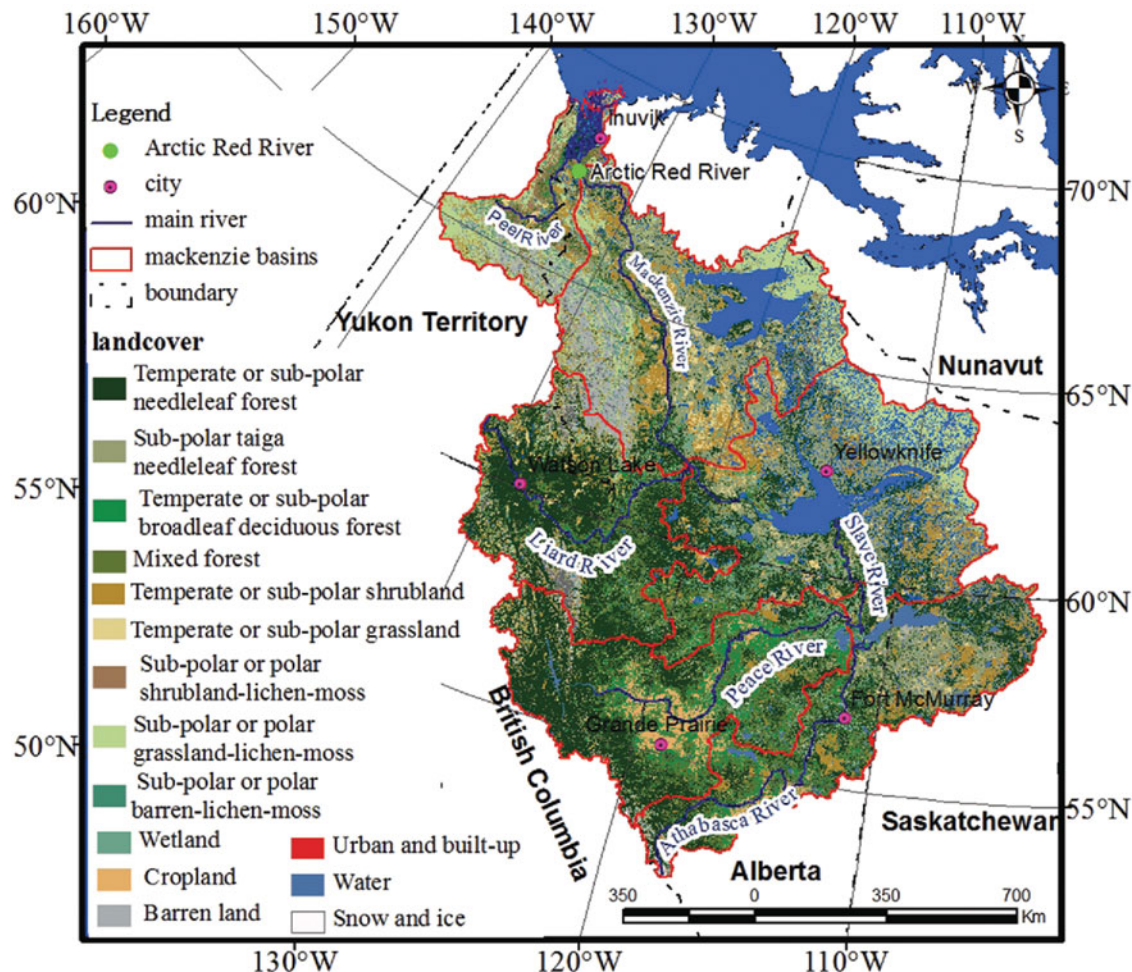
FIG. 1. Land cover types over the Mackenzie Basin.

Mackenzie River. It focuses on the basin scale to investigate the main features of watershed hydrology, ecology, and their linkages. It quantifies the seasonal cycles of basin vegetation and discharge and examines their space–time consistency and changes over the summer growing season. The main objective of this investigation is to explore and establish a relationship between stream flow and NDVI over a large northern watershed. The methods and results of this work will improve our understanding of hydrology and ecosystem interactions over the broader northern regions.

BASIN, DATA, AND METHODS

The Mackenzie is the largest North American river (Figure 1). It drains an area of 1.8 million km², about 1/5 of the total land area of Canada. Its headwaters, covering parts of British Columbia, Alberta, Saskatchewan, and the Northwest Territories, collect a vast system of rivers that flow into Great Slave Lake, from which the Mackenzie River flows in a north-westerly direction for about 1600 km before discharging (about 330 km³/year) through the Mackenzie Delta into the Beaufort Sea. Basin physical features vary widely from the Rocky Mountain system to the flat, mainly treeless barren lands. Permafrost and wetland cover approximately 75% and 49%, respectively, of the basin. Pingos and pattern-ground features associated with continuous permafrost are found in the north, whereas agriculture and forestry are important economic activities in the southern parts of the basin. The basin has several climatic regions, including cold temperate, mountain, subarctic, and arctic zones. Mean annual temperatures vary from around $-10\,^\circ$C to $4\,^\circ$C, and annual precipitation ranges from more than 1,000 mm in the southwest to about 200 mm along the Arctic coast, averaging about 410 mm/year (Woo and Thorne 2003). There are large lakes in the basin that provide natural regulation to the system. One reservoir was built in the Peace River, its operation may substantially influence the water level fluctuations in the Great Slave Lake but does not significantly affect the flow conditions at the lower Mackenzie (Woo and Thorne 2003; Peters and Prowse 2001).

Streamflow records observed at the watershed outlet reflect basin integration of both natural variations and human-induced changes, such as changes of land cover/land use and regulations of large dams within the watersheds (Yang, Ye, and Kane 2004; Yang, Ye, and Siklomanov 2004; Yang et al. 2002). Discharge data collected at the river mouth are particularly important because they represent freshwater input to the ocean and are often used for basin-scale water balance calculations, climate change analysis, and validations of land surface schemes and GCMs over large spatial scales (Yang, Marsh, et al. 2014; Yang, Shi, et al. 2014; Wang et al. 2014). It is important to understand the fundamental characteristics, including temporal variations and changes of streamflow over the basins. The Water Survey of Canada (WSC) has gauged the Mackenzie River at several locations along its main trunk. The flow at Arctic Red River combines the regimes of its subbasins. Discharge data collected at this location, before the river branches into many tributaries, is considered as the total flow for the Mackenzie system. The daily flow records for this station, available at the hydrometric database (HYDAT) for the period of 1982–2006, have been obtained and used for this study.

The NDVI data derived from the Advanced Very High Resolution Radiometer (AVHRR) and processed by the Global Inventory Monitoring and Modeling Studies (GIMMS)[1] have been used extensively to examine the vegetation patterns and changes over the northern regions (Kim et al. 2014; Peng et al. 2012; Wang et al. 2011; Bhatt et al. 2010). The dataset has been organized at 8-km resolution with a half-month maximum NDVI value from 1982 to 2006. This dataset has been processed to minimize corruption of vegetation signals from atmospheric effects, scan angle effects, cloud contamination, volcanic eruption, and effects of varying solar zenith angle. The NDVI is generally expressed on a scale range from 0.0 to 0.7, and the higher value indicates the denser vegetation (Pinzon 2002; Pinzon et al. 2005; Pinzon et al. 2014; Tucker et al. 2005). Lower values generally contain more spurious signals (e.g., from the snow, lakes, and soil background, etc.), which are not related to photosynthetically active vegetation. Previous studies show that NDVI values greater than 0.05 can more accurately extract the vegetation information (Fretwell et al. 2010; Myneni et al. 1995). Therefore, in this study, the NDVI values above 0.05 are considered useful to represent vegetation activities over the Mackenzie Basin.

In this study, we apply various statistical approaches for data analyses. Daily data were used to generate half-month discharge time series to compare with the NDVI records. We calculate the long-term means and standard deviation for the NDVI and discharge data. We also carry out trend analysis and statistical significance test to identify long-term changes in streamflow and vegetation. We apply a linear regression to the records to determine its changes as a function of time (year). The total

[1]Available at http://daac.gsfc.nasa.gov/.

trend is defined by the difference of flows or NDVI shown on the regression line between the first year and the last year. The standard Student's t-test is used to determine the statistical significance of the trends. We then compare the results of trend and spatial difference between river discharge and NDVI via regression and correlation analyses. We also examine the extreme high/low flow years and the associated NDVI conditions. We compare our results with other relevant studies in the northern regions. From this, we generate new information and knowledge to advance our understanding of linkage and interaction between the vegetation pattern and basin discharge regimes and changes.

RESULTS

Seasonality of NDVI and Discharge

Figure 2 shows the basin-mean half-month NDVI and discharge within a year for the period 1982–2006. The NDVI pattern looks like a Gaussian shape over the seasons, with the values ranging from 0.15 in winter to 0.67 in summer. During the period of January to the 1st half of April, and November to December, the NDVI is almost constant, around 0.14. These periods are the cold seasons with a stable snow cover and basin temperature below –10 °C. There is little vegetation activity in the cold season with snowcover. During the 2nd half of April to the end of October, the NDVI values are usually above 0.20; these are the times when air temperatures are above 0 °C and vegetation is active (Olthof and Latifovic 2007). For instance, the NDVI increases rapidly after the 2nd half of April and reaches the maximum value of 0.67 in the 2nd half of July; it then declines gradually until October. In the rising stage from the 2nd half of April to late July, the rate of NDVI change is the largest. The rising rate of NDVI reached 1.58 in May, which is much higher relative to other months, such as 0.72 for the 2nd half of April to 1st half of May and 1.12 during the 2nd half of May to 1st half of June. This dramatic increase in May indicates the onset of vegetation growth over most parts of the Mackenzie Basin. In other words, the 1st half of May can be regarded as the beginning of growing season over the basin. In the summer (June to August), the NDVI remains high, around 0.54–0.67. However, the NDVI in September has the largest drop by 1.72. This decline is significantly faster than the other half-months, i.e., 0.08 for the 2nd half of August to 1st half of September and 0.07 for the 2nd half of September to the 1st half of October. The decreases in NDVI values suggest that vegetation gradually wilts after the 2nd half of September over the Mackenzie Basin. Therefore, the period from May to September can be regarded as the growing season of vegetation in the Mackenzie Basin. The NDVI phenology is similar to temperature seasonality in the northern regions. The peak NDVI correlates with highest temperature, with a lag of 10 days following the maximum temperature (Olthof and Latifovic 2007). In this study, we focus mainly on vegetation change and its relationship with river discharge during the growing season.
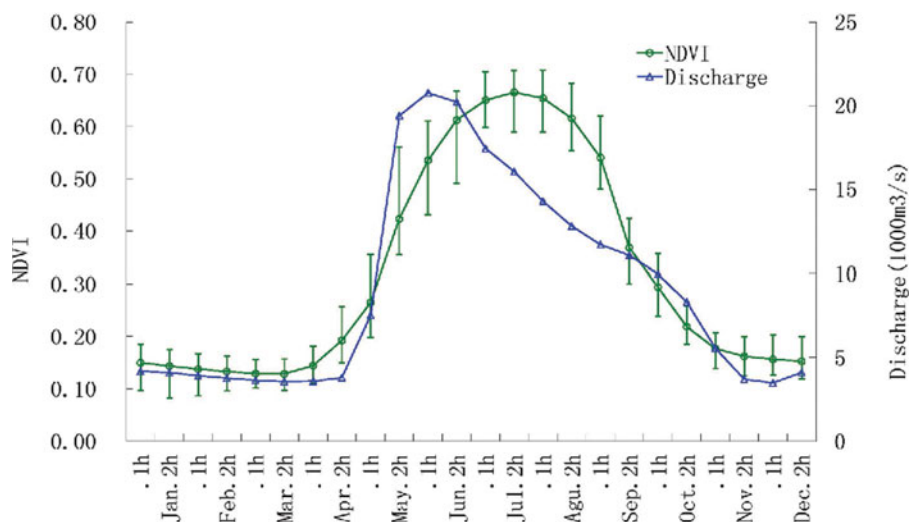
FIG. 2. Basin mean NDVI and discharge for the period 1982 to 2006.

To reveal the spatial pattern of vegetation change in the growing season over the Mackenzie Basin, average NDVI during 1982 to 2006 was calculated for each grid cell for all the half-month during May to September (Figure 3). Over most areas of the basin, the NDVI increases from May to July and reaches the maximum at the 2nd half of July, and then it gradually reduces until the 2nd half of September. There are significant spatial variations in the NDVI values over the basin (Figure 3). In the river valley and lowland areas around the Liard River midstream and Peace River downstream, the vegetation type is dominated by deciduous forest (Figure 1). These are areas with the maximum NDVI value above 0.70. Moreover, the vegetation in these areas and the surrounding regions begins to turn green earlier than other regions in the basin. Over the Mackenzie Mountains and Rocky Mountains, vegetation cover is relatively poor, with the maximum NDVI being less than 0.40 in the midsummer. Due to cold temperatures in the mountain regions, the vegetation has a relatively short growing season. In fact, vegetation generally starts turning green at the 2nd half of May and begins turning brown at the 1st half of October in these regions. The growing season in these regions generally lasts for about 4 months, about 1 month shorter than the other regions. NDVI variation is large, above 0.4 between the maximum and minimum values, over the growing season in the northeast parts of the basin.

The half-month mean discharge of the Mackenzie River is very low and generally maintains at about 4,000m³/s during January to April (Figure 2). Discharge increases in the 1st half of May; the rate of change is sharp at the 2nd half of May, and flow reaches the highest amount (21,000 m3/s) in the 1st half of June. The process of discharge increasing is quick, reaching the highest peak within 3 half-months. High flow period runs from May to September as the result of spring snowmelt and summer rainfall contributions. Discharge decreases very slowly from the peak value, and this process lasts about 5 months, until

the 2nd half of October, due mainly to many large lakes and their storage in the basin.

The patterns of NDVI and discharge are similar in the cold season, because they are both low and change very little over the winter. At the beginning of the growing season (after the 1st half of May), along with a dramatic increase of the discharge from the 1st half of May to the 1st half of June, the NDVI rises rapidly. The timing of NDVI rise closely couples with the process of rapid discharge increase during this period. The discharge reached the peak in the 1st half of June, but NDVI is the highest in the 2nd half of July; there is a lag of 1.5 months between flow and NDVI peaks. Discharge declines after the 1st half of June, but the deceasing trend is slow or steady. It is worth noting that the discharge remains above 10,000 m³/s during the declined stage of June to September. This suggests sufficient water and soil moisture supply for vegetation growth, even though discharge has decreased significantly since the 1st half of June. After the 2nd half of September, both NDVI and discharge gradually declined with a similar pace.

Trends of NDVI and Discharge

Trend analyses for growing season NDVI during 1982 to 2006 indicate a decreasing tendency for most warm months, except the 2nd half of April to the 1st half of May and the 2nd half of September (Figure 4). The significant decreases occurred mainly in July to August. In this period, the total NDVI reductions over the 25 years were greater than 0.028 (about 4% of the mean NDVI), especially with a greatest decrease by 0.04 ($p < 0.075$) in the 1st half of August (or 6% of the mean NDVI). A significant increase was found in the 2nd half of September and the 1st half of October, with the cumulative change of 0.02 ($p < 0.338$) and 0.03 ($p < 0.108$), respectively, or 5% and 11%, relative to the mean NDVI. The positive changes in the 2nd half
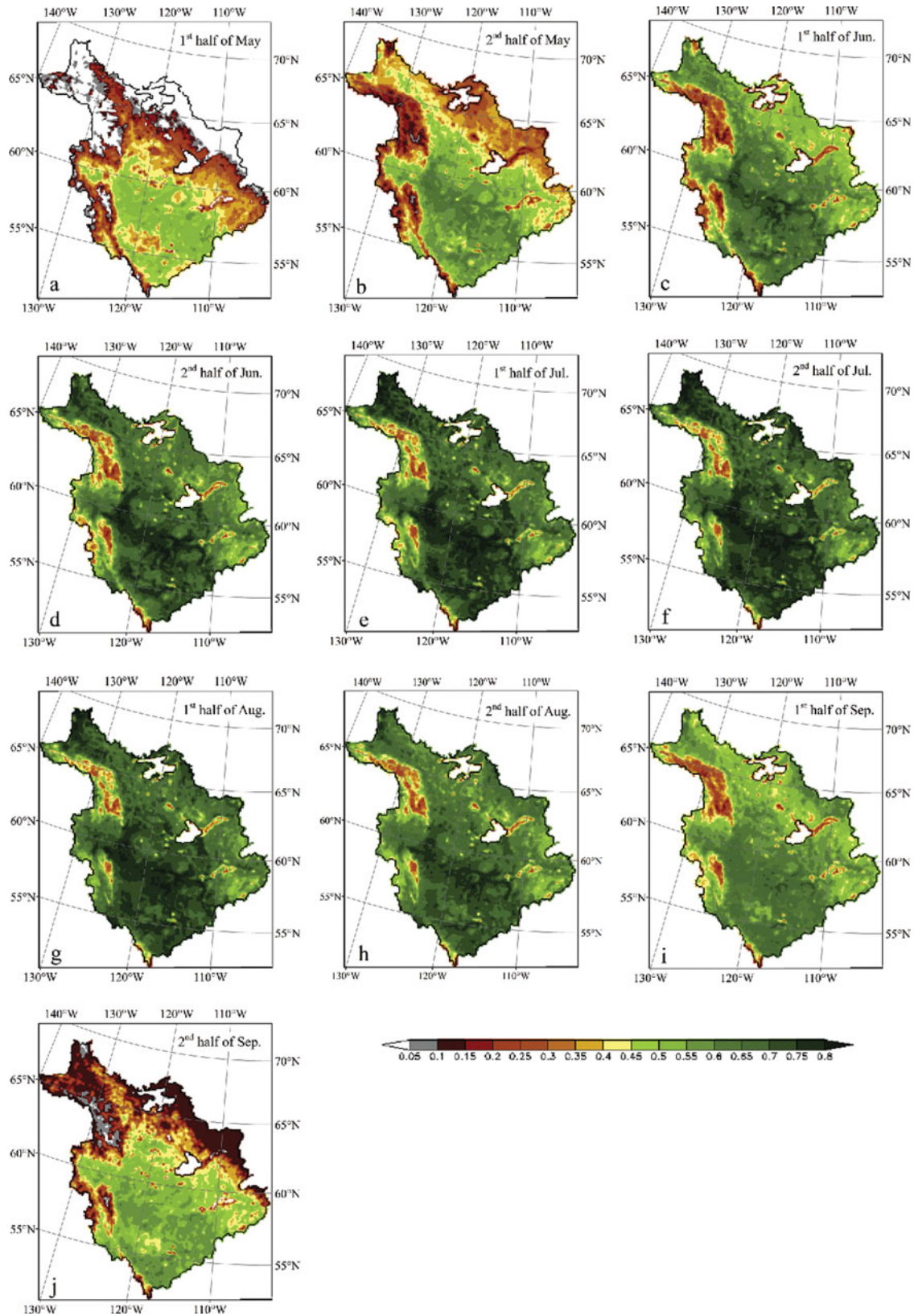
FIG. 3. Half-month mean NDVI from May to September during 1982 to 2006 over the Mackenzie Basin. Note: (a) for 1st half of May, (b) for 2nd half of May, (c) for 1st half of June, (d) for the 2nd half of June, (e) for 1st half of July, (f) for 2nd half of July, (g) for 1st half of August, (h) for 2nd half of August, (i) for 1st half of September, and (j) for 2nd half of September.
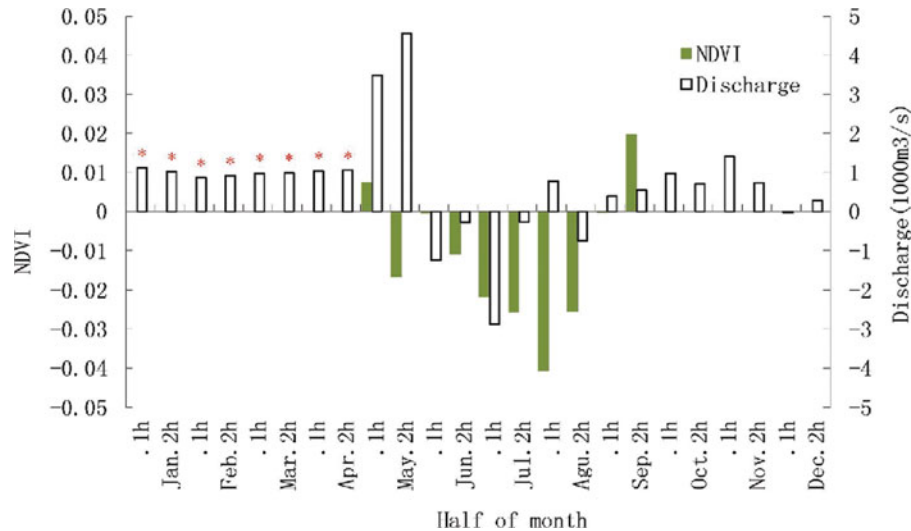
FIG. 4. Trends of discharge and mean NDVI over the Mackenzie Basin during 1982 to 2006. The bars with an asterisk (*) indicate trends significant at 0.05 level.

of April to the 1st half of May were weak, less than 0.02 over the study period.

River discharge increased in most times of the year except in summer; there are only 2 and a half months with the general decreasing trends. The most significant increase occurred in May, with the total trends of 7,500 m³/s/a ($p < 0.085$) and 19,000 m³/s/a ($p < 0.144$), or 46% and 23%, respectively, of the mean discharge. Discharge in the 1st half of July shows most significant decrease by approximately 2,800 m³/s/a ($p < 0.242$), or about 16% of the average flow.

The trends of NDVI and discharge are similar or different depending on the time of the year. It is worth noting that, during the growing season from May to September, the NDVI trends are clearly corresponding with the discharge changes most of the time. For example, the NDVI decreased at the 2nd half of June, the 1st half of July, the 2nd half of July, and the 2nd half of August, and discharge trends usually showed negative changes for the same time periods. The NDVI increased in the 1st half of May or the 2nd half of September and the discharge increased as well. It seems clear that vegetation change is closely related to discharge variation over the growing season in the study area. This result suggests that a higher flow in the warm season may lead to better vegetation production over the basin.

To reveal the details of NDVI changes in summer, we calculate the trend of NDVI data for all the cells in the basin during 1982 to 2006 (Figure 5). The results show NDVI decreases in the summer season over the Mackenzie River. The areas with NDVI declined are more than 80% of the basin, with the decreasing rate of 0.01–0.0 6 per decade (Figure 5a) or about 0%–25% per decade (Figure 5b). The NDVI decreased over the flat and lowland areas, except Mackenzie Mountains, Rocky Mountains, and the northeastern edge of the basin. Significant negative changes, exceeding –0.04%/10yr or –5%/10yr (Figure

5c), are located mainly in the areas west and east of Great Slave Lake and downstream regions. The NDVI decreases in these regions are mainly related to climate variation and fluctuation, particularly longer and warmer growing seasons in a warming climate that promotes surface drying, drought, and fires in the summer season over the northern regions, including northern Canada (Kim et al. 2014; Piao et al. 2014).

NDVI-Discharge Correlation

In order to further explore the relationship between NDVI and discharge in the Mackenzie Basin, we calculated the linear correlation coefficients between half-month mean NDVI and discharge during the growing season. River discharge reflects basin water supply and storage. Spring flow is the highest contributor to the annual flow; higher spring flows usually lead to high summer flows, thus providing necessary water to support vegetation activities from spring to the later season. Yi et al. (2014) found that spring hydrology affects soil respiration in relatively wet boreal and arctic ecosystems and plays an important role in determining summer net carbon uptake. It is possible that river flow in the earlier season may affect vegetation in the later season. For example, in the Yellow River Delta, China, there is a close correlation between NDVI and streamflow during the entire growing season, but the positive correlation has a time lag of about a month (Jiang et al. 2013). To consider this factor, we calculate the lag correlation between river flow and NDVI, with flow leading up to 3 months.

Table 1 presents the results of correlations. The "1h" and "2h" in the second row indicates the 1st or 2nd half-month NDVI, 0 in the first column represents the 1st half of May discharge, and –1 represents the 2nd half of April discharge, i.e., one half-month
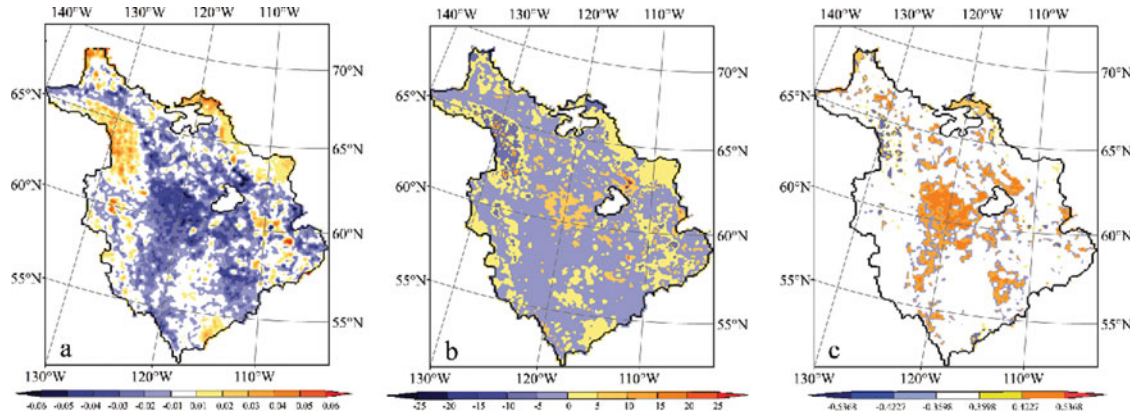
FIG. 5. (a) Summer NDVI trend, (b) percentage change per 10 years, (c) with significant level above 0.10, during 1982 to 2006 in Mackenzie Basin.

time step ahead of the NDVI. The significances of correlation are coded with different colors in the table. The results show 2 sensitive periods for NDVI to respond or associate to discharge in the Mackenzie Basin: the periods of May to June, and the period of the 2nd half of July to the 1st half of August. It is important to note that these two periods are, respectively, the times of NDVI rapid rise and decline from the peak values. In the first period, the NDVI increases rapidly from the 1st half of May to the 2nd half of June, with the most significant increase during the 1st half of May to the 1st half of June after vegetation onset. There is a strong correlation between the 1st half of May NDVI and discharge (with 0 lag). NDVI in the 2nd half of May and the 1st half of June also correlate closely with discharge in the1st half of May. This result suggests that the discharge in the 1st half of May is a key factor affecting vegetation growth, not only for the 1st half of May, but also for later time, i.e., the 2nd half of May and the 1st half of June. This seems reasonable, because summer moisture supply plays a major role in limiting vegetation productivity due to frequent summer droughts and stronger evaporative demands (Kim et al. 2014; Ma et al. 2012; Peng et al. 2011). Spring flow reflects basin water storage and

soil moisture condition that could influence vegetation processes over the whole summer.

For the 2nd sensitive period of the 2nd half of July to the 1st half of August, the NDVI is related closely to discharge for the 2nd half of June to the 1st half of August, with the lag time from 0 to 5 half-months. The correlation coefficients suggest that vegetation growth during the 2nd half of July to the 2nd half of August strongly responds to river flow in the 2nd half of June and the 1st half of July. The coefficients between the 1st half of July discharge and the 2nd half of July, the 1st half of August and the 2nd half of August NDVI have the highest values of 0.4610 ($p < 0.05$), 0.5245 ($p < 0.05$) and 0.7015 ($p < 0.01$). The correlation between the 2nd half of August NDVI and discharge at the 2nd half of June to the end of August are all significant at 0.01 level, with the coefficients greater than other half-months. Vegetation in the 2nd half of August is most sensitive to the discharge during June to August. There is a long lag of NDVI behind flow; this seems to suggest the cumulative effect of river flow to basin water storage and maybe soil moisture variation over the summer season. Evaporation is relative high in the summer season; it can reduce or limit the water

TABLE 1
Lag correlation coefficients between half-month NDVI and discharge during the growing season.

Half Month / Lag	May		Jun		Jul		Aug		Sep	
	1h	2h	1h	2h	1h	2h	1h	2h	1h	2h
0	0.7262	0.3933	−0.1808	−0.0347	0.2848	0.4065	0.4795	0.5727	0.4772	0.0620
−1	0.5200	0.6053	0.4143	0.1136	0.2968	0.4610	0.4426	0.6427	0.4952	0.0870
−2	0.4150	0.4350	0.4440	0.2861	0.2219	0.4663	0.5245	0.6359	0.5325	0.0103
−3	0.1904	0.2881	0.4421	0.2004	0.2058	0.1202	0.4635	0.7015	0.3978	0.0426
−4	0.0647	−0.0259	0.4208	0.3610	−0.0745	−0.0120	0.3067	0.5584	0.3568	−0.0118
−5	−0.0240	−0.1194	0.2823	0.4227	0.2075	−0.3092	−0.1272	0.4428	0.2471	−0.0198
−6	−0.0568	−0.1348	0.2076	0.3797	0.3125	0.0633	0.4553	0.0387	0.0582	0.0147

Note: Colors in cells represent the correlation coefficients at various significant levels, i.e. ■ 0.01, ■ 0.05, □ 0.01, ▨ −0.05. 1h and 2h stand for 1st and 2nd half of the month.
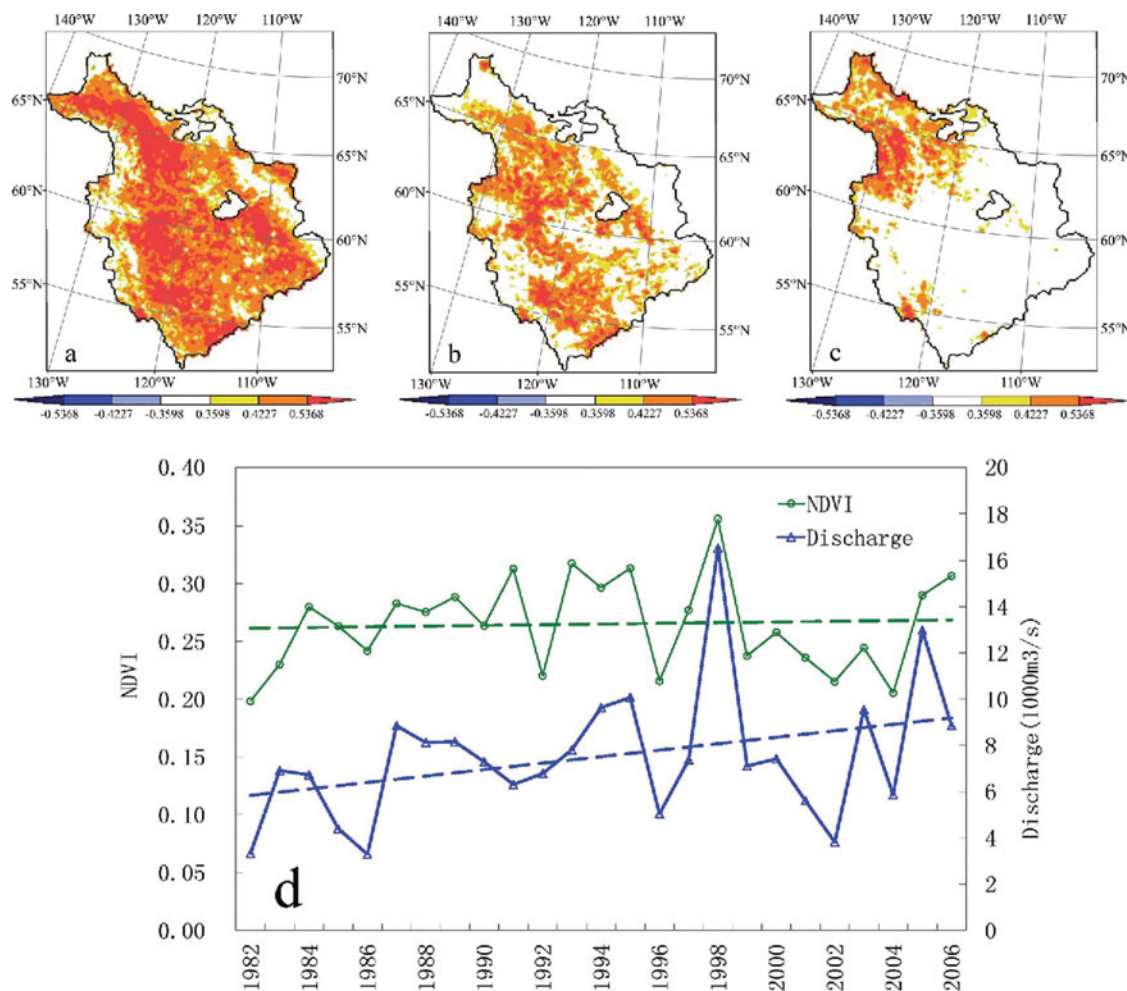
FIG. 6. Correlation coefficients between (a) the 1st half of May discharge and NDVI in the 1st half of May, (b) 2nd half of May and (c) 1st half of June over the Mackenzie Basin, and (d) 1st half of May discharge and basin mean NDVI during 1982 to 2006.

availability to plants. Study shows that recent summer warming since the late 1980s has increased evapotranspiration demand and, consequently, summer drought severity in the northern region (Barichivich et al. 2014). A lengthening of the evaporative period may lead to a buildup of soil water deficit over the early and middle portion of the growing season (Jepsen et al. 2012), thus limiting plants' growth. Over the Mackenzie Basin, both flow and NDVI have decreasing trends in summer during the study period (Figure 4), indicating less basin storage and soil moisture or more frequent dry conditions negatively affecting vegetation activities. To better understand the results from this analysis, more efforts and data, particularly vegetation information, such as growth rate in summer for different vegetation types within the large basin, will be necessary.

As a critical period, the 1st half of May discharge has a strong effect on the NDVI from the 1st half of May to the 1st half of June. To understand the spatial pattern of the relationship, we calculated the correlation coefficients between the 1st half of May discharge and NDVI at the 1st half of May, the 2nd half of May, and the 1st half of June over the Mackenzie Basin. Figure 6 shows the grids with correlations significant at 0.10, 0.05, and 0.01 levels. As seen in Figure 6a, NDVI is related closely to discharge variation in most areas except the regions of Mackenzie Mountain and the Rocky Mountains, and the region of the eastern edge of the basin. Moreover, nearly 50% of the basin has correlation significant at above 0.01 level. Figures 6b,c show that the 1st half of May discharge also widely and strongly relates to the 2nd half of May and the 1st half of June NDVI over the basin, although the correlations are slightly weaker than the 1st half of May. This result is consistent with the basin mean correlations in Table 1. It is important to note that the correlations from the 1st half of May to the 1st half of June not only shrink markedly in size, but also change in geographic patterns. Specifically, the correlation patterns between the 1st

half of May discharge and the 2nd half of May NDVI are similar to that of the 1st half of May NDVI. The areas have shrunken especially for the high correlations (significant at the 0.01 level). The high correlation zones are located mainly in the valley and lowland areas of the Mackenzie River, Peace River, and Slave River. To the 1st half of June, the influence of the 1st half of May discharge on vegetation still clearly exists (Figure 6c), although both the area and significance decline sharply.

Figure 6d presents the 1st half of May discharge and mean NDVI records over the Mackenzie Basin from 1982 to 2006. These data suggest a clear increasing discharge trend by $139 m^3/s/a$ (significant at 0.10 level), whereas the NDVI shows a very weak upward trend. Despite the weak trend consistency, there are consistent interannual fluctuations between discharge and NDVI data. Over the study period, when the discharge was higher (or lower), the NDVI was correspondingly higher (or lower). This association was especially clear in 1986, 1996, and 1998. In these years, both discharge and NDVI were the highest in 1998, significantly lower in 1986, and 1996. Synchronous variation in both records further confirms a direct relationship between discharge fluctuation and vegetation growth over the basin. However, for 1990 and 2006, the flows were lower with above normal NDVI values over the basin. These years were associated with lower-than-normal peak snow water equivalent (SWE) over the Mackenzie Basin (Yang, Shi, et al. 2014). The lower SWE may lead to lower soil moisture conditions in these 2 years. Summer rainfall perhaps was normal to higher to support vegetation grow in these 2 years. Given data limitation, it is difficult to examine all possible factors in 1 study. Our ongoing effort will consider other factors and processes.

The 2nd half of August is the time when the NDVI sensitively responds to discharge from June to August (Table 1). Similar to the 1st half of May, we calculated the correlations between NDVI and discharge for all the cells within the basin. Figure 7 shows the maps of correlation coefficients between the 2nd half of August NDVI over the Mackenzie Basin and discharges from June to August. These maps display the correlation patterns with significance at 0.10, 0.05, and 0.01 levels.

For the 2nd half of August discharge (Figure 7a), the high correlation zone is located mainly in the region west of the Great Slave Lake and southern parts of the basin. For the 1st half of August discharge, the high correlation zone moved to south and northwest of the Great Slave Lake and midstream and downstream of the Peace River (Figure 7b). The correlation patterns in the 2nd half of July are similar to those in the 1st half of July, but with a clear westward and southward shift in location (Figure 7c). Relative to the 1st half of August, the area of high correlations in the 2nd half of July significantly increased in the region southwest of the Great Slave Lake, weakly decreased to the south of the Great Slave Lake, and obviously declined to the north. For the 1st half of July discharge, the high correlation zone moved and spread toward the northwest (Figure 7d), i.e.,

to the west of the Great Slave Lake, and along the Mackenzie River valley between the Great Slave Lake and Great Bear Lake. The high correlation zone for the June discharge, located in the central part of the basin, shrunk continuously toward the north (Figure 7e and Figure 7f).

The high correlation zone of the 2nd half of August NDVI to discharge during June to August shifted from northwest to southeast. The spatial patterns of high correlations between the 2nd half of August NDVI and discharge in June to August indicated that vegetation growth in the 2nd half of August responded tightly to river flow in most areas of the Mackenzie Basin, although responses in different areas were sensitively related to different periods. Over the summer season as a whole, the areas of high correlations (significant above 0.10 levels) reach the maximum in the 1st half of July, suggesting that the 1st half of July discharge has the most significant influence on the 2nd half of August NDVI.

Figure 7g displays the 1st half of July discharge and the 2nd half of August basin mean NDVI during 1982 to 2006. The interannual fluctuations are very consistent between these 2 variables, because both strongly decreased over the study period. During 1982 to 2006, the extremely high/low discharge years match exactly with the highest/lowest NDVI years. For example, 1988 was the year with highest flow and higher NDVI, and 1995 was the year with the lowest flow and lower NDVI. This consistency of interannual variations between the 1st half of July discharge and 2nd half of August NDVI is a good evidence of NDVI association to the river flow. In other words, the precondition of water storage and availability (represented by river flow variations) is the key factor to plant growth and processes over the warm season.

Extreme Flows and NDVI Conditions

Based on the preceding analysis, it seems clear that discharge in spring and summer affects vegetation growth over the Mackenzie Basin. In order to understand the linkage between river flow and vegetation processes, we examined the highest and lowest peak flow years during 1982 to 2006 and the corresponding NDVI conditions. Figure 8 illustrates the seasonality of NDVI and discharge in 2 extreme years. Discharge conditions were very different between 1995 and 1992, particularly during the warm season. The flows in 1995 were very low, with the peak discharge of about $138,000 m^3/s$ in the 2nd half of May. However, the flows in 1992 were very high, with the peak flow of $289,000 m^3/s$ in the 1st half of June. The difference in peak discharge between these 2 years is about $10,900 m^3/s$; relatively, the peak flow in 1995 is about 56% of that in 1992.

Summer flow in 1995 was remarkably less than that in 1992; discharge in the 1st half of July to the 2nd half of August in 1995 account for only 43%, 47%, 50%, and 52% of that in 1992. In comparison to the mean discharge (see Figure 2b), the maximum discharge in the 2nd half of May in 1995 was
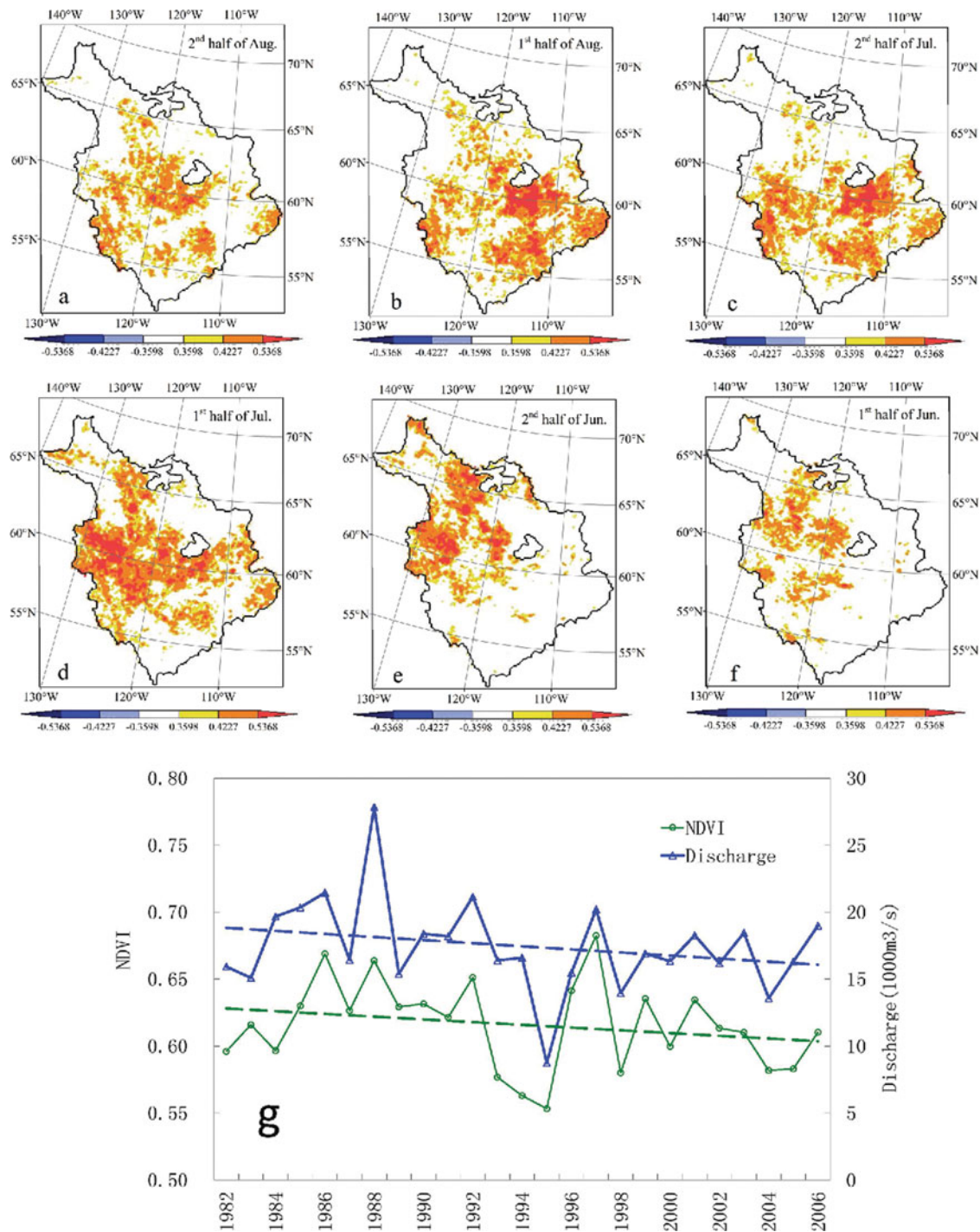
FIG. 7. Correlation coefficients between (a) the 2nd half of August NDVI and the discharge at the 2nd half of August, (b) 1st half of August, (c) 2nd half of July, (d) 1st half of July, (e) 2nd half of June, and (f) 1st half of June over the Mackenzie Basin, and (g) the 1st half of July discharge and the 2nd half of August basin NDVI during 1982 to 2006.
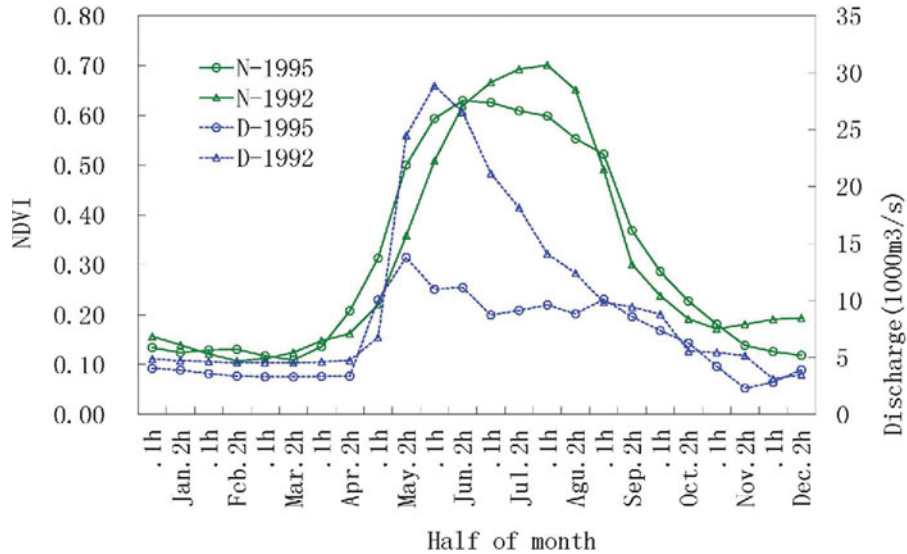
FIG. 8. Extreme discharge and basin mean NDVI for 1992 and 1995.

one month earlier than the normal year, whereas the peak flow in the 1st half of June in 1992 was very high with its timing near the normal. The huge differences in both the peak flow (56%) and its timing (1 month) between 1995 and 1992 may have affected the vegetation activities over the basin, because there is a close positive correlation between NDVI and discharge at the stage of rapid vegetation growth during spring and early summer.

The NDVI patterns were very different between 1995 and 1992 over the warm season, particularly during the 1st half of July to the 1st half of August. In 1992, with higher flow, the NDVI increased continually after the 2nd half of June and reached the peak (0.71) in the 1st half of August. It is important to note that the NDVI remained higher (above 0.4) for 3.5 months in this summer, maybe due to better water supply with higher flow in the spring. To the contrary, in 1995, with lower discharge, the NDVI peak was lower (0.63) and earlier in the 2nd half of June, and it decreased slowly to the fall. The year of 1995 had the lowest NDVI in the 2nd half of August during the study period; the maximum NDVI is clearly lower than that in 1992.

In comparison with mean NDVI, the maximum NDVI in the 2nd half of June in 1995 was a month earlier than the normal year, and the peak NDVI in the 1st half of August in 1992 appeared 1 half-month later than normal. The difference in the peak NDVI between the 2 years is about 0.07; relatively, the peak value in 1995 is about 90% of that in 1992. The period from the 1st half of July to the 1st half of September is the key period for vegetation production. The summer NDVI in 1995 was remarkably less than that in 1992; NDVI at the 1st half of July, 2nd half of July, 1st half of August, 2nd half of August, and 1st half of September in 1995 account for only 93%, 87%, 84%, 81%, and 84% of that in 1992. The comparisons of extreme flow years support that the discharge during summer/spring will directly impact vegetation, i.e., higher discharge will benefit

vegetation growth and high production over the basin. This result is generally consistent with other analyses of the NDVI relationship with precipitation over the northern regions (Kim and Wang 2007) and the Tibetan Plateau (Ding et al. 2007).

SUMMARY AND DISCUSSION

Based on the analyses of long-term discharge and NDVI data, this study found a strong seasonal consistency between NDVI and discharge over the Mackenzie River Basin. The flow-NDVI association is particularly strong in the early growing season (in May). During this period, discharge rapidly rises and reaches the peak, and NDVI increases around the 1st half of May and reaches the maximum in the 2nd half of July. In the mid- and late summer, both discharge and NDVI decline gradually. Correlation analyses identify 2 sensitive periods when NDVI significantly responds to discharge variations: the period of May to June and the 2nd half of July to 1st half of September. In the first period, the half-month NDVI highly correlates to the 1st half of May discharge, indicating that spring flow has a strong influence on vegetation growth in the early growing season. Spatially, almost all the basin shows a high correlation, except Mackenzie Mountain and the Rocky Mountains and the region near the eastern edge of the basin. For the 2nd period of the 2nd half of July to the 1st half of September, the NDVI relates closely to discharge with lags of 0–5 half-months. Trends analyses suggest that river discharge during 1982 to 2006 increased in most seasons except summer. The most significant increase, by 46% and 23% occurred during the 2 half-months in May. Discharge in the 1st half of July decreased by about 16%. The NDVI trends during the growing season from May to September clearly correspond to discharge changes. For example, the NDVI decreased by 4%–6% in the 2nd half of June, 1st half of July, 2nd half of July, and 2nd half of August, when discharge had negative changes during the study period. This result clearly indicates

that seasonal vegetation change is closely related to discharge variation, and the higher flow in the spring–summer season will lead to better vegetation production over the Mackenzie Basin. In addition, examination of extreme flow years and corresponding NDVI conditions over the basin also reveals that a low runoff year was associated with a lower basin NDVI with an earlier maximum, whereas the higher flow year was linked with a higher NDVI and a longer growth season.

This study is a basin-scale exploration of vegetation–flow relationship in the northern regions. It is important to note that the Mackenzie River is a large watershed with diverse climatic, physical, and ecological conditions. This river is about 3,000 km long and flow travel takes weeks from upstream to downstream. This study is very important to identify large-scale linkage between basin flow regime and vegetation patterns. It also closely relates to basin climate and hydrology change analyses, such as Yang, Marsh, et al. (2014), Yang, Shi, et al. (2014), and Woo and Thorne (2003). In order to better understand hydrology and vegetation interactions, it is useful to carry out similar analyses at the subbasins within a big basin. It is also necessary to link basin/subbasin study with local-/plot-scale observations, including snow cover, soil moisture patterns/changes, and their relationship with vegetation processes. Ecosystem modeling and advanced remote sensing techniques are also powerful tools to advance our understanding of northern hydrology and ecosystems.

The selections of time scale for basin hydrology and climate investigations are also important. A weekly step has been used for the analyses of snow cover and runoff relationship over the large northern basins (Yang et al. 2009; Yang et al. 2003). This study chooses the half-month step mainly because of NDVI data availability. The results seem to be reasonable for the large basin. Weekly-to-decadal time scales may be useful to better relate this work with snowmelt and river flow processes, particularly over the spring season. There are MODIS, NDVI, or SPOT vegetation products at 10-day time steps since 2001 and 1998, respectively. These data are relatively shorter than the NDVI data, and they may be subject to uncertainties, especially in the cold regions due to impact of snow cover. It would be, however, useful to consider the weekly or decadal data in the future analyses, in order to compare and validate the results from this work.

The results of this study suggest that river flow reflects water availability over a basin. Studies also show river flow is an index for storage changes over a basin (Brutsaert 2008; Ye et al. 2009), although not the best but easy to obtain with long-term records. Regional or basin storage is difficult to measure or determine. In addition to soil moisture, snow cover is important for the northern regions as the main storage. Snow cover affects regional hydrology and vegetation processes (Yang et al. 2009; Yang, Shi, et al. 2014; Yi et al. 2014). GRACE data can determine the total storage changes over large regions (Swenson et al. 2006; Velicogna et al. 2012). Given the total storage, the key challenge is then to determine the amount of water available to plants and trees. It is a critical question as far as how to obtain this information from river discharge records and available GRACE or snow

cover (SWE) data. Effort is necessary to study the interactions among basin snow cover, discharge, and vegetation dynamics through coupled models and field observations.

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