Streamflow response to seasonal snow cover extent changes in large Siberian watersheds

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[1] This study uses remotely sensed long-term (1966–1999) weekly snow cover extent data to investigate snowmelt runoff response to seasonal snow cover change in the large Siberian watersheds (Ob, Yenisei, and Lena basins). It quantified the seasonal cycles and variations of snow cover extent and river streamflow and identified a clear correspondence of river streamflow to seasonal snow cover extent change; i.e., an association of low streamflow with high snow cover extent during the cold season and an increase in discharge associated with a decrease of snow cover extent during the melt periods. This study also examined and compared the weekly mean streamflow with the weekly basin snow cover extent for the study period. The results revealed a very strong linkage between the streamflow and snow cover extent change during the spring melt season over the large Siberian watersheds and developed a statistically significant weekly runoff-snow cover relation. This relation suggests a practical procedure of using remotely sensed snow cover information for snowmelt runoff forecasting over the large northern watersheds. Analyses of extreme (high/low) streamflow cases (years) and the associated snow cover conditions indicate an association of high (low) flood peak with late (early) snowmelt in the Ob and Yenisei basins. Comparisons of snowmelt timing with peak flow show different associations between these two variables among the large Siberian rivers. These results demonstrate that the NOAA weekly snow cover extent data are useful for understanding and predicting streamflow changes in the Arctic regions. Snow cover water equivalent data/products obtained by remote sensing technology and in situ snow observations are currently being examined for what we expect will eventually improve hydrologic forecasts over the large northern watersheds. *INDEX TERMS:* 1860 Hydrology: Runoff and streamflow; 1863 Hydrology: Snow and ice (1827); 1827 Hydrology: Glaciology (1863); 1640 Global Change: Remote sensing; *KEYWORDS:* runoff, snow cover, Siberian rivers

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1. Introduction

[2] Arctic rivers are important to global ocean and climate systems. River discharge is a primary driver of the Arctic Ocean freshwater budget, as discharge from the Arctic rivers contributes as much as 10% to the upper 100 meters of water column of the entire Arctic Ocean. The amount and variation of this freshwater inflow critically affect the salinity and sea ice formation, and may also exert significant control over global ocean circulation [*Aagaard and Carmack*, 1989]. Arctic hydrologic systems exhibit large temporal variability due to large-scale changes in atmospheric circulation [*Proshutinksy et al.*, 1999; *Walsh*, 2000; *Semiletov et al.*, 2000]. This variation significantly influences the cross-shelf movement of water, nutrients and sediments. Examination of streamflow hydrology and change in the major northern river basins and their relations to surface climate and atmosphere are critical to better understand and quantify the atmosphere-land-ocean interactions in the Arctic and consequent global impacts.

[3] Snow cover is one of the critical land memory processes that significantly affect atmosphere, hydrology and ecosystems in the high latitude regions. Snow cover melt and associated floods are the most important hydrologic event of the year in the northern river basins [*Kane*, 1997]. Studies show that snowmelt has started early over the recent decades in the northern regions, such as Canada, Alaska, and Siberia, associated with warming in winter and spring seasons [*Whitfield and Cannon*, 2000; *Brabets et al.*, 2000; *Serreze et al.*, 2000; *Zhang et al.*, 2001; *Lammers et al.*, 2001; *Yang et al.*, 2002]. This change in the melt pattern may indicate a hydrologic regime shift over the high latitudes [*Yang et al.*, 2002; *Serreze et al.*, 2002]. Our current knowledge of large-scale snowmelt processes and their interaction with climatic change and variation is incomplete, particularly for Arctic regions where we do

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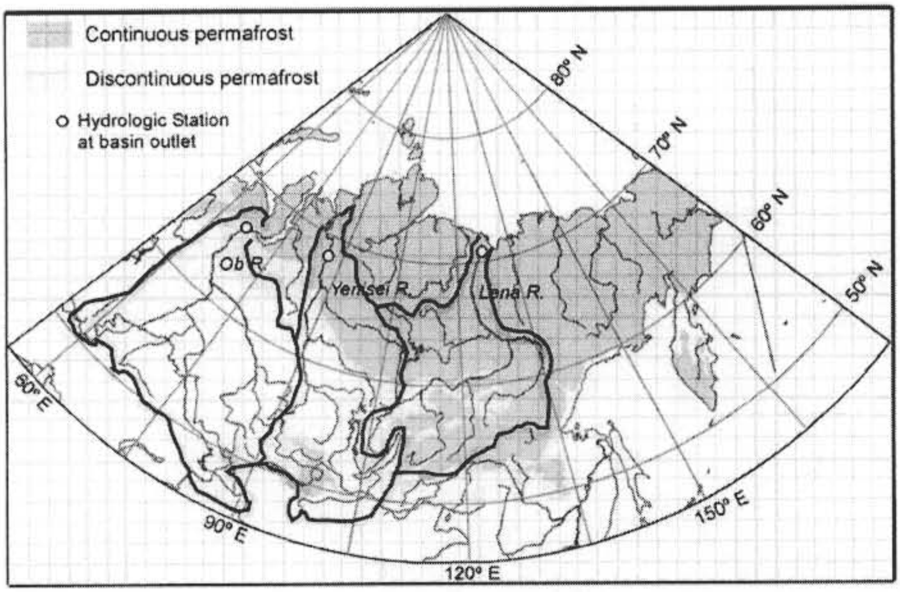

Figure 1. The three major rivers (Lena, Yenisei, and Ob) in Siberia. Also shown are permafrost distribution, basin boundaries, hydrologic stations at the basin outlets, and NOAA snow cover grid (89 × 89) interpretation. See color version of this figure in the HTML.

not have enough ground-based observations [*Vörösmarty et al.*, 2001]. This limits our ability of predicting potential changes in the hydrology system under a warming climate in the high latitude regions.

[4] Studies demonstrate that the timing and magnitude of discharge of northern rivers is strongly allied with cold season snow mass storage and subsequent melt [*Rango*, 1997; *Cao et al.*, 2002]. Remote sensing data/products have been very useful to cold region climate and hydrology investigations [*Massom*, 1995]. For instance, the NOAA snow cover maps are useful for hydrologic and snowmelt runoff models [*Rango*, 1996, 1997; *Rango and Shalaby*, 1999]. However, there have been relatively few validation efforts in the large Arctic watersheds. This paper uses the weekly NOAA snow cover extent data to study the streamflow hydrology in large Siberian rivers. The emphasis of this research is to examine the streamflow response to snow cover extent change during the spring melt season, so as to determine the potential of using remotely sensed snow cover information to enhance our capability of snowmelt runoff modeling and forecasting over large northern river basins. The results of this study will improve our understanding of the impact of climate variation and change on cold region hydrologic processes.

2. Data Sets and Method of Analysis

[5] The Lena, Yenesei and Ob rivers are the three largest rivers in the Arctic. The combined discharge from these rivers contributes more than 45% of total freshwater flow into the Arctic Ocean [*Shiklomanov et al.*, 2000; *Prowse and Flegg*, 2000; *Grabs et al.*, 2000]. These large, northern flowing watersheds stretch from midlatitudes to the Arctic coast (Figure 1). Their drainage areas range from 2,400,000 to 3,000,000 km^2 and are mostly underlain by continuous and discontinuous permafrost [*Brown and Haggerty*, 1998; *Zhang et al.*, 1999]. Since the late 1930s, hydrological observations in the Siberian regions, such as discharge, stream water temperature, river-ice thickness, dates of river freeze-up and break-up, have been carried out by the Russian Hydrometeorological Service and the observational records are quality-controlled and archived by the same agency [*Shiklomanov et al.*, 2000]. Some of these data are now available to this study for the period of 1930s to 1999. In this analysis, long-term daily discharge records collected at the basin outlet stations are used (Table 1).

[6] The NOAA weekly snow cover maps based on visible data, despite some limitations, are quite reliable at many times and in many regions. They are important for polar region climate, snow and ice studies [*Steffen et al.*, 1993]. The establishment of the weekly snow cover data set over the Northern Hemisphere permits quantitative assessments of changes and variations in regional snow cover extent [*Robinson et al.*, 1993; *Robinson and Frei*, 2000; *Frei and Robinson*, 1998, 1999; *Serreze et al.*, 1993; *Clark et al.*, 1997]. These maps extend back to late 1966, and have recently had several inconsistencies rectified. The NOAA snow cover maps are readily available and inexpensive. They have been widely used for hydrologic and climatic analyses in the cold regions, such as development of basin snow cover depletion curves [*Rango*, 1996, 1997; *Skaugen*, 1999], study of snow cover changes in large northern watersheds [*Cao et al.*, 2002], input snow cover data to regional hydrologic and snowmelt runoff models [*Rango*, 1997], and validation of climate model performance [*Yang et al.*, 1999; *Frei and Robinson*, 1998].

[7] In this study, we use the NOAA weekly snow cover data to generate basin mean snow cover extent time series over the large Siberian rivers (Figure 1) for the period 1966–1999. On the basis of these weekly records, we

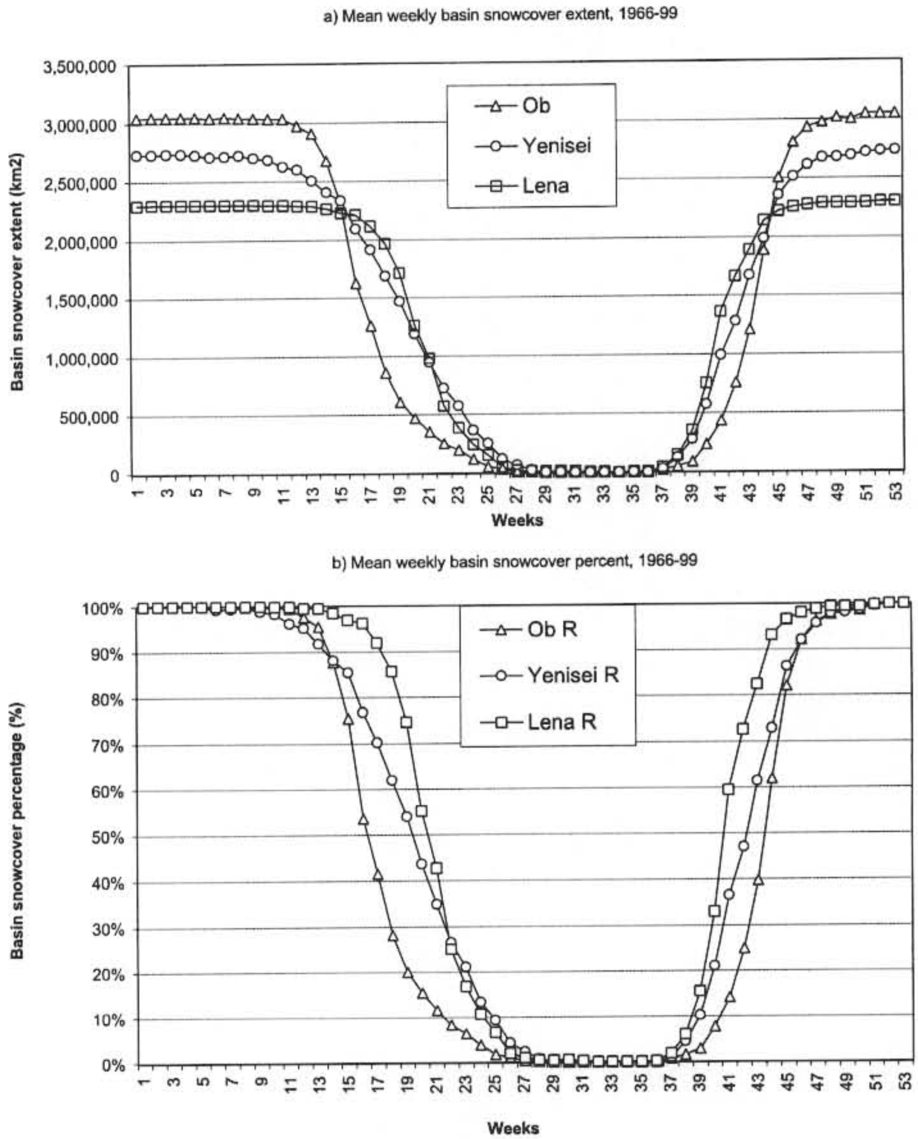

Figure 2. Mean weekly snow cover extent over the three basins, (a) basin snow cover area and (b) basin snow cover fraction. See color version of this figure in the HTML.

examine the seasonal changes of snow cover extent, by defining the weekly snow cover climatology, determining the dates of snow cover formation/disappearance and duration of snow cover/snow-free days, and quantifying the rates of snow cover change during the accumulation and melt seasons. We also generate long-term weekly discharge time series from the daily streamflow data collected at basin outlets and use the weekly data to describe the seasonal runoff changes, including runoff regime, rates of streamflow rise and peak flow during the melt period. We calculate the weekly correlation of streamflow with basin snow cover extent, and determine the consistency between snow cover and runoff changes over the seasons. Furthermore, we identify extreme snowmelt runoff cases and examine their correspondence with snow cover conditions. These analyses define the weekly relation between snowmelt runoff and snow cover changes for the large watersheds in Siberia. In addition to streamflow and snow cover data, basin mean monthly precipitation and temperature time series were created based on gridded global data sets [*Jones*, 1994; *Hulme*, 1991], and used to explain the response of river hydrology to seasonal snow cover changes.

3. Results

3.1. Weekly Snow Cover Extent (SCE)

[8] The seasonal cycle of the weekly snow cover extent over the Siberian regions is presented in Figure 2. It shows that both the accumulation and ablation processes are different among the large watersheds mainly due to temperature and precipitation differences between the western and eastern Siberian regions. Snow cover begins to form around late September (weeks 37–38) in Siberia. During the accumulation period, Ob basin mean temperatures are

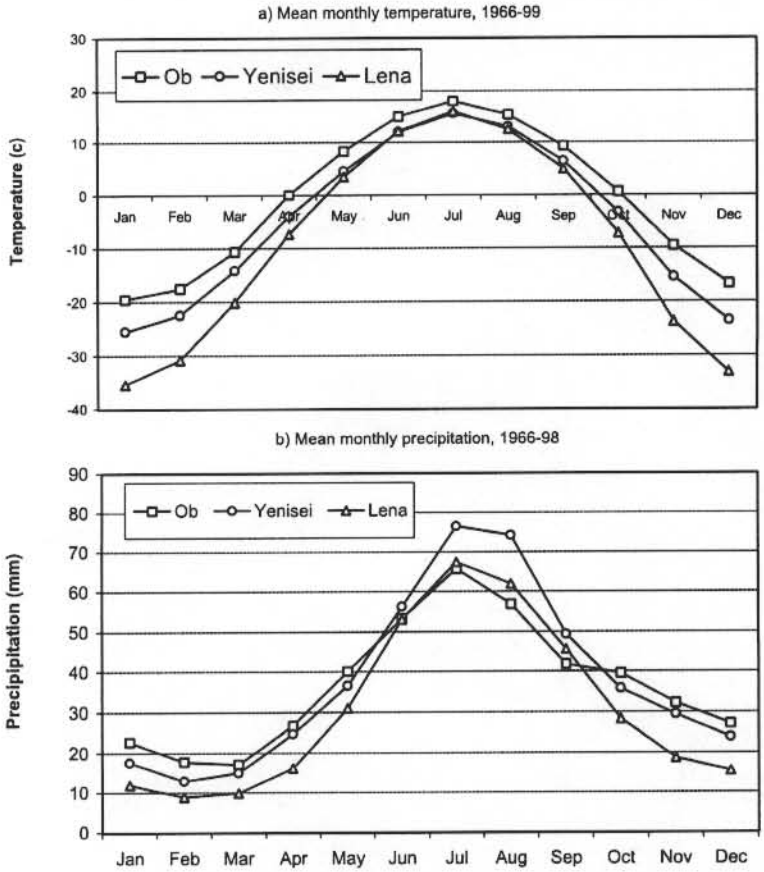

Figure 3. Long-term basin mean monthly (a) temperature and (b) precipitation over the three watersheds. See color version of this figure in the HTML.

warmer by 4.5°C in September and 7.8°C for October, respectively, relative to the Lena watershed (Figure 3a). Similar amounts of precipitation (45 mm) fall in both basins in September (Figure 3b). The cooler temperature during late September over the Lena basin leads to the early formation of snow cover over eastern Siberia. The rate of snow cover (development) accumulation is higher over the Lena basin, moderate in the Yenisei watershed, and lower across the Ob river. Snow cover reaches the maximum extent around early November (week 45) over the Lena basin, and during late November to early December (weeks 47–49) for both the Yenisei and Ob basins. During weeks 45–49, the three basins become completely snow covered. The maximum snow cover maintained until early March (around weeks 9–13).

[9] Because of much warmer winter and spring temperatures over western Siberia (Figure 3a), the snowmelt season starts there around middle March (week 12–13) and gradually progresses eastward. The delay of the onset of snowmelt is 3–4 weeks over the Lena basin. The rate of snow cover depletion is very high during late April to mid-May (weeks 16–19) in the Ob basin, with the snow cover reduced by 55% within 4 weeks. Lena basin snow cover melts strongly during May (weeks 19–23), while the Yenisei river snowmelt is slower, reducing only 50% snow cover area in more than 7 weeks (Figure 2). In addition to temperature influence, this difference in snow cover depletion among the regions is likely associated with amounts of snowpack accumulation over the winter season. Climate data indicate higher winter precipitation over western Siberia (Figure 3b), and long-term ground observations also show that the basin mean maximum snow depth at the end of winter season is 39 cm in the Ob river and 32 cm in the Lena basin, respectively [*Ye et al.*, 1998]. To illustrate snow cover melt processes over Siberia, Figure 4 displays an example of weekly snow cover changes over a typical melt season in 1999. The three river basin boundaries are also shown.

[10] It is interesting to note that, despite the regional differences in snowpack accumulation and climate, the snowmelt season ends at almost the same time in the three basins. The snow cover disappears around early July over Siberia, i.e., week 27 in the Ob basin and week 28 in both the Yenisei and Lena basins. The snowmelt periods vary from 17 weeks in the Ob basin, 16 weeks in the Yenisei watershed, to 14 weeks in the Lena catchment (Figure 2). The shorter melt season suggests a faster melt of the shallow snow cover over eastern Siberian regions. Interannual variations of the weekly SCE are generally small over the study areas, with the standard deviation ranging from 1–15% of the mean weekly snow cover in both winter (complete snow cover) and summer season (free of snow cover), and large (20–45%) during both spring and fall transition periods. The variability of snow cover extent in

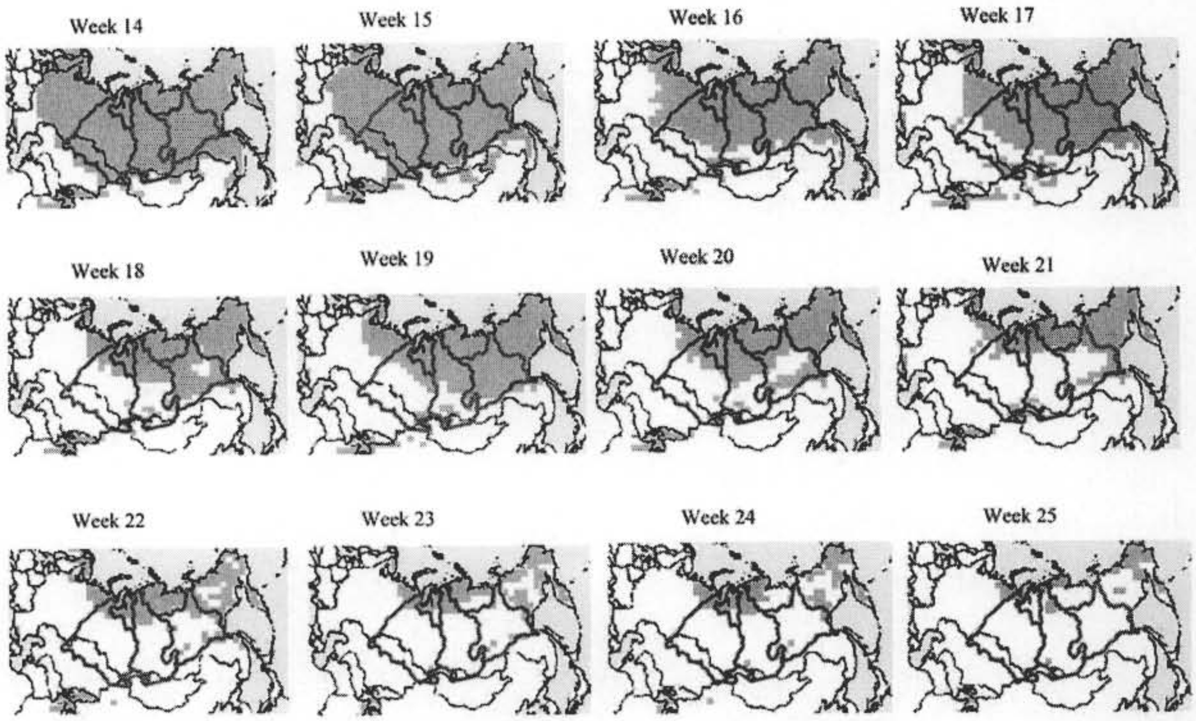

Figure 4. Changes of snow cover extent over Siberia, during weeks 14–25, 1999. The three river basin boundaries are also shown. See color version of this figure in the HTML.

late spring and early fall seasons is particularly large, standard deviation being up to 50–150% of the weekly means, when the southern potions of the basin were snow free, and the northern parts of the basins were covered by snow due to late melt or early snow accumulation.

[11] Results of snow cover trend analyses are presented in Figure 5. They show the total trends in snow cover extent defined by a linear regression over the study period 1966–1999. The Ob river snow cover had no significant trends during January to early March (weeks 51–11), while snow cover extent increased during late March to April (weeks 12–17). The largest increase (13,860 km^2, or 0.46% of the basin area) was found, statistically significant at 85% confidence, in early April during week 15. Strong

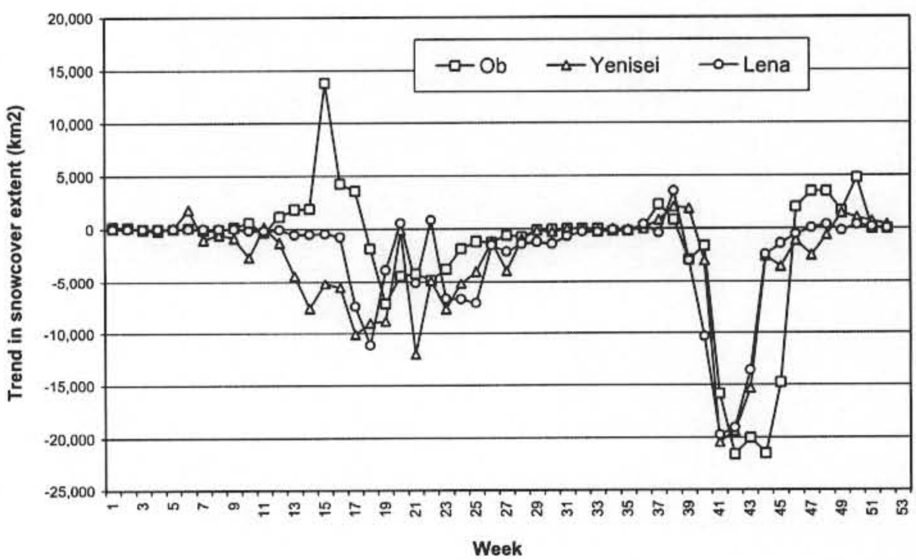

Figure 5. Trend of weekly snow cover extent over the large Siberian rivers, 1966–1999. See color version of this figure in the HTML.

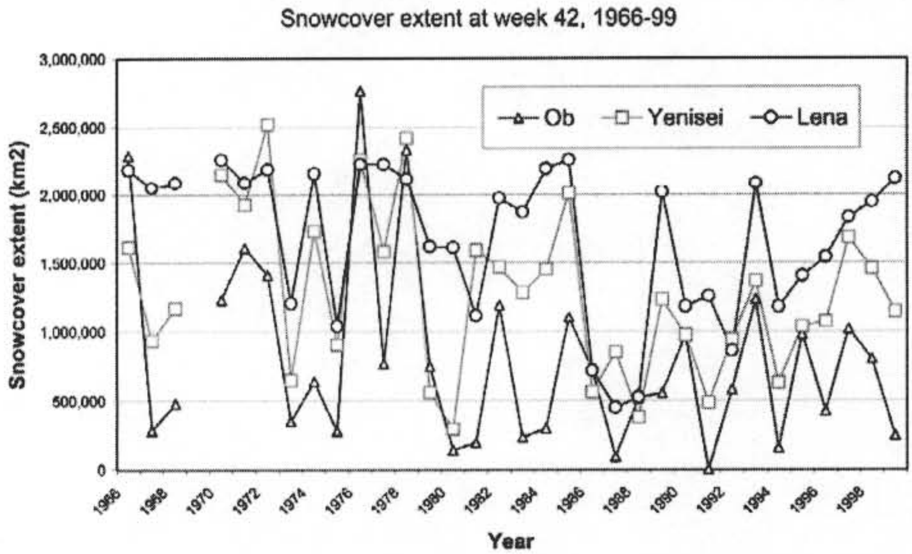

Figure 6. Time series of weekly basin snow cover extent for week 42, 1966–1999. Snow cover data are missing during weeks 23–43 in 1969. See color version of this figure in the HTML.

decreasing trends by 0.05–0.15% of the basin area were discovered during weeks 18–24 (May and June), and weak downward trends (less then 0.01% of the basin) was detected in July (weeks 26–28). No significant trends were detected for August (weeks 32–35), while upward trends were discovered in early September (weeks 36–37). Late September and October (weeks 38–44) had downward trends (0.05–0.70% of the basin area, statistical significance 90–95%), followed by weak upward trends (0.05–0.10% of the basin) in both November and December (weeks 45–52). The Yenisei basin did not have any significant SCE trends during December to early March (weeks 49–11). Negative trends (0.40–4.40% of the basin area) were found during mid-March to early July (weeks 12–28), with the strongest (statistical significance at 95%) decease by 12,000 km^2 in week 21. Little changes occurred from mid-July to September (weeks 29–40), and October (weeks 41–43) had a strong decrease by about 0.25–0.40% of basin area and November (weeks 45–48) had a weak decline (0.05–0.15% of basin). The Lena basin showed little changes in SCE during November to mid-April (weeks 45–16), and decreasing trends (by 0.02–0.50% of basin area, statistically significant at 85–95% confidence) in late April to June (weeks 17–25). No trends were found during July to mid-September (weeks 26–38), and strong decreases (0.11–0.86% of the basin area) were identified during late September to October (weeks 39–44), with the largest decline close to 20,000 km^2 during week 41.

[12] Differences and similarities in snow cover extent changes among the basins can be explained by spatial variation in climate changes, particularly temperature and precipitation. Decreases of snow cover extent during spring melt periods in both the Yenisei and Lena basins were mainly due to temperature warming, as no major change in precipitation was observed [*Wang and Cho*, 1997]. Increase in snow cover areas during early spring season in the Ob basin was caused by a strong increase in winter precipitation over western Siberia [*Wang and Cho*, 1997], that outweighs the warming-induced early melt of snow cover. On the other hand, strong decreases in SCE during fall season seen over the three watersheds (Figure 6) were perhaps owing to a tendency toward a warmer and drier fall season, particularly over the west parts of Siberia.

3.2. Weekly Streamflow Regime

[13] The seasonal cycle of weekly discharge at the basin outlets is presented in Figure 7. They generally show a similar seasonality across Siberia, i.e., a low flow period during November to April (weeks 45–17) and a high runoff season from June to October (weeks 23–43), with the maximum discharge occurring usually in June (weeks 23–26) due to snowmelt floods. There are however noticeable differences in runoff regime between the basins mainly due to different climate and permafrost conditions over Siberia.

[14] Snowmelt causes the river streamflow to increase at week 17 in both the Ob river and the Yenisei watershed, and week 20 (the 2nd week in May) in the Lena catchment, respectively. The early rise of discharge in the Ob river is associated with the early melt of snow cover over western Siberia (Figures 2 and 4). As snowmelt progresses, discharge continues to rise in these watersheds. In comparison to the Ob river, the rate of streamflow rise is very high in the Yenisei and Lena basins, up to 38,000 m3/s and 40,000 m3/s per week, respectively. As a result, the Lena river reaches to the peak flow in 3 weeks since the start of the snowmelt season. Streamflow of the three rivers peaks at the same time, i.e., week 24 (or the 3rd week in June), when the basins are still covered by a patchy snowpack (6.4% snow cover in the Ob river, 21.1% in the Yenisei basin and 32.1% in the Lena basin). The magnitudes of the weekly peak flow range from 44,600 m3/s for the Ob river to 157,000 m3/s for the Yenisei river, and 177,000 m3/s for the Lena basin, respectively. Streamflow drops at the end of the snowmelt season, although summer heavy rainfall events generate floods over the basins. The rate of discharge decrease is much slower in the Ob river than the Lena and Yenisei basins.

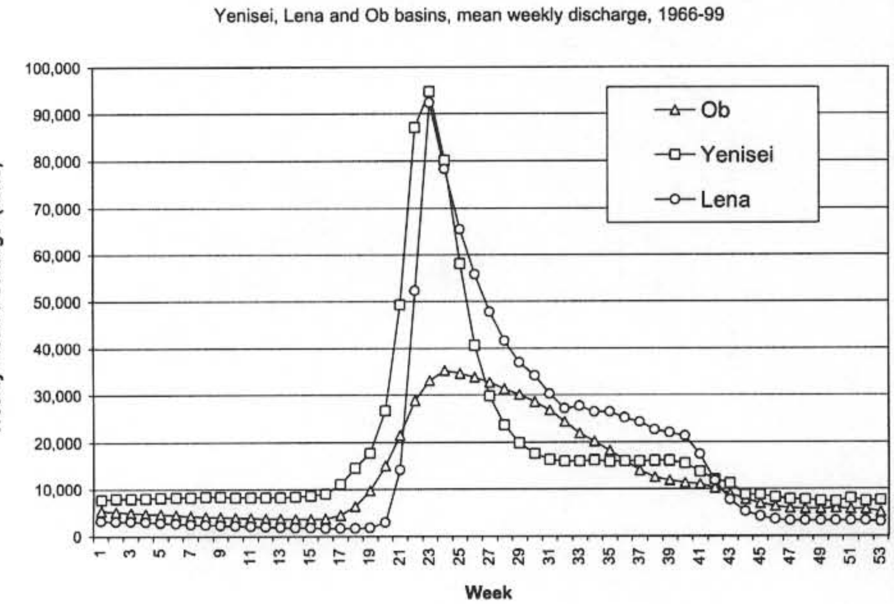

Figure 7. Long-term mean weekly discharge for the three large rivers, 1966–1999. See color version of this figure in the HTML.

Discharge reaches the minimum during weeks 44–46. The magnitudes of the low discharge are similar between the Yenisei and Ob rivers, about 2500 m3/s, but very low for the Lena basin, only 800 m3/s.

[15] Generally watersheds with high permafrost coverage have low subsurface storage capacity and thus a low winter runoff and a high summer peak flow [*Woo*, 1986; *Kane*, 1997]. The Lena river, underlain by continuous permafrost (80–90%), has a very low winter flow and a very high peak flow in June, about 55 times greater than the minimum discharge. Yenisei river, with 60–70% permafrost, shows a higher winter flow and a lower peak runoff, about eightfold increase over the minimum discharge in April. The Ob basin, on the other hand, with about 30–40% permafrost coverage, has the highest winter streamflow and the lowest peak discharge, about half of the other two rivers or ninefold the winter minimum runoff. The quicker responses of streamflow to snowmelt and faster decrease of streamflow after snowmelt in the Lena and Yenisei rivers are also related to a lower subsurface storage capacity due to a higher percentage of permafrost coverage in the central and eastern Siberian regions. The interannual variation of weekly runoff is generally small in the cold season and large over summer months mainly due to rainfall storm activities and associated floods.

3.3. Weekly Relation of Streamflow Versus Snow Cover Extent

[16] The weekly long-term means of snow cover extent and river streamflow records are shown in Figure 8. It clearly indicates a response of river runoff to seasonal snow cover changes, i.e., an association of low streamflow with high snow cover extent during the cold season, and an increase in discharge associated with a decrease of snow cover extent during the melt periods. To quantify the relation between river runoff and basin snow cover extent variations, we examine and compare the weekly mean streamflow with the weekly basin snow cover extent for the period 1966–1999. The results generally confirm a very strong linkage between the streamflow and snow cover extent during the spring melt season over the large Siberian watersheds (Figure 9).

[17] In the early melt period (weeks 18–20), Lena basin snow cover extent reduces from 90% to 55%. Most of the meltwater is stored in ponds, lakes and river valleys. River ice breaks up around this time in the upper parts of the basin, but streamflow at the basin outlet does not show a clear response due to ice jams in the river valleys. As snowmelt progresses (weeks 21–22), snow cover area decreases to 45–14%, releasing more water to satisfy the surface storage. During this period, river channels open up in the northern parts of the watershed and discharge at the basin mouth starts to rise. This response of streamflow to snowmelt is reflected by a strong negative correlation between runoff and snow cover extent. In the late melt period (weeks 23–25), streamflow response to snowmelt weakens due to reduced snowmelt runoff contribution. Similar processes exist for the Yenisei basin. The strongest weekly relation between runoff and snow cover extent is seen during weeks 20–22, when 25–45% of the basin is covered by a patchy snowpack. The Ob river, however, is slightly different. Streamflow strongly correlates with snow cover extent during weeks 18–20, with the mean basin snow cover being 15–18%. The lower percentage of snow cover during these weeks of high correlation may reflect a higher surface and subsurface storage capacity due to high percentage of wetlands and less permafrost in the Ob basin.

[18] A weekly relation between runoff and snow cover extent was derived by a regression analysis for the warm season. It shows that the correlation between runoff and snow cover change is the strongest during the snowmelt period. The relationship for the Ob basin is most significant

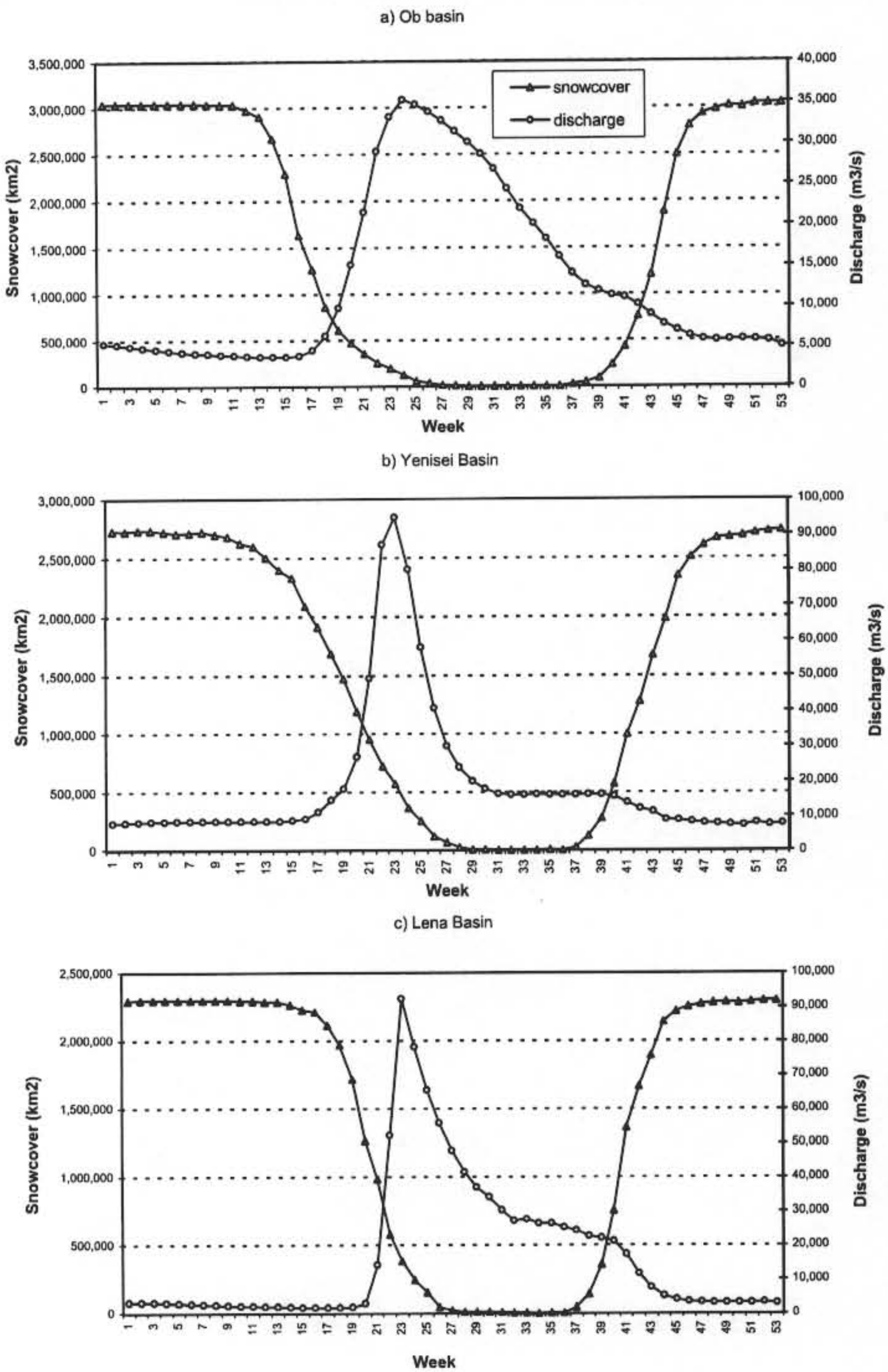

Figure 8. Comparison of seasonal cycles between weekly snow cover and streamflow over the three rivers. See color version of this figure in the HTML.

during weeks 17 to 19. The dependency of runoff to snow cover is very strong during weeks 21 and 22 in the Lena river, while the Yenisei basin has a close relation in weeks from 20 through 22 (Figure 10). The regressions derived here explain 20–45% of runoff variability, although they are statistically significant at 99% confidence. It is useful to quantify these relations, as they suggest a practical procedure of using remotely sensed SCE information for snowmelt runoff predicting over the large northern watersheds.

3.4. Extreme Discharge and Associated Snow Cover Condition

[19] Discharge data show that weekly snowmelt peak floods vary widely among years. To understand this

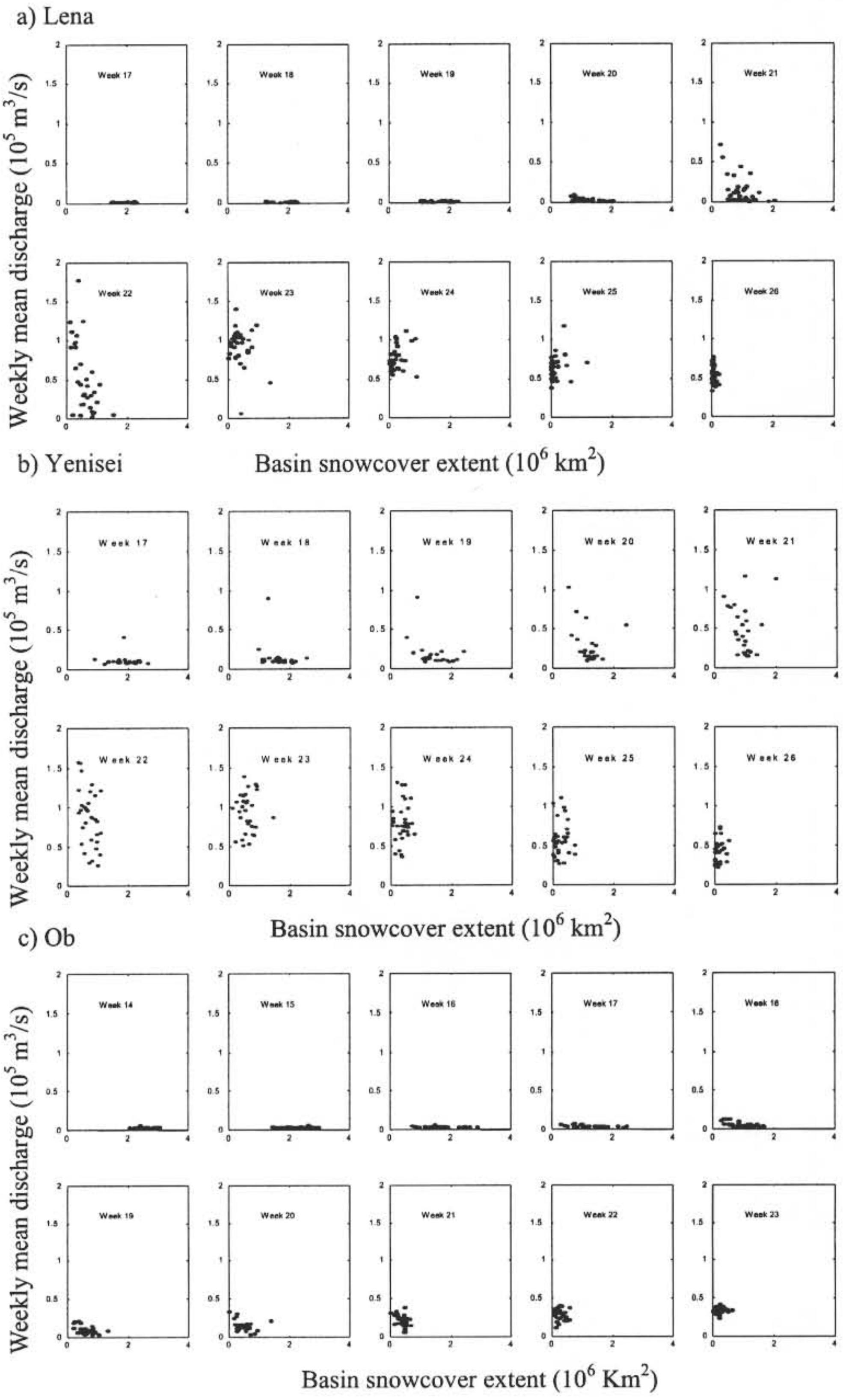

Figure 9. Scatterplots of weekly streamflow versus weekly basin snow cover extent for the selected weeks in a year, 1966–1999.

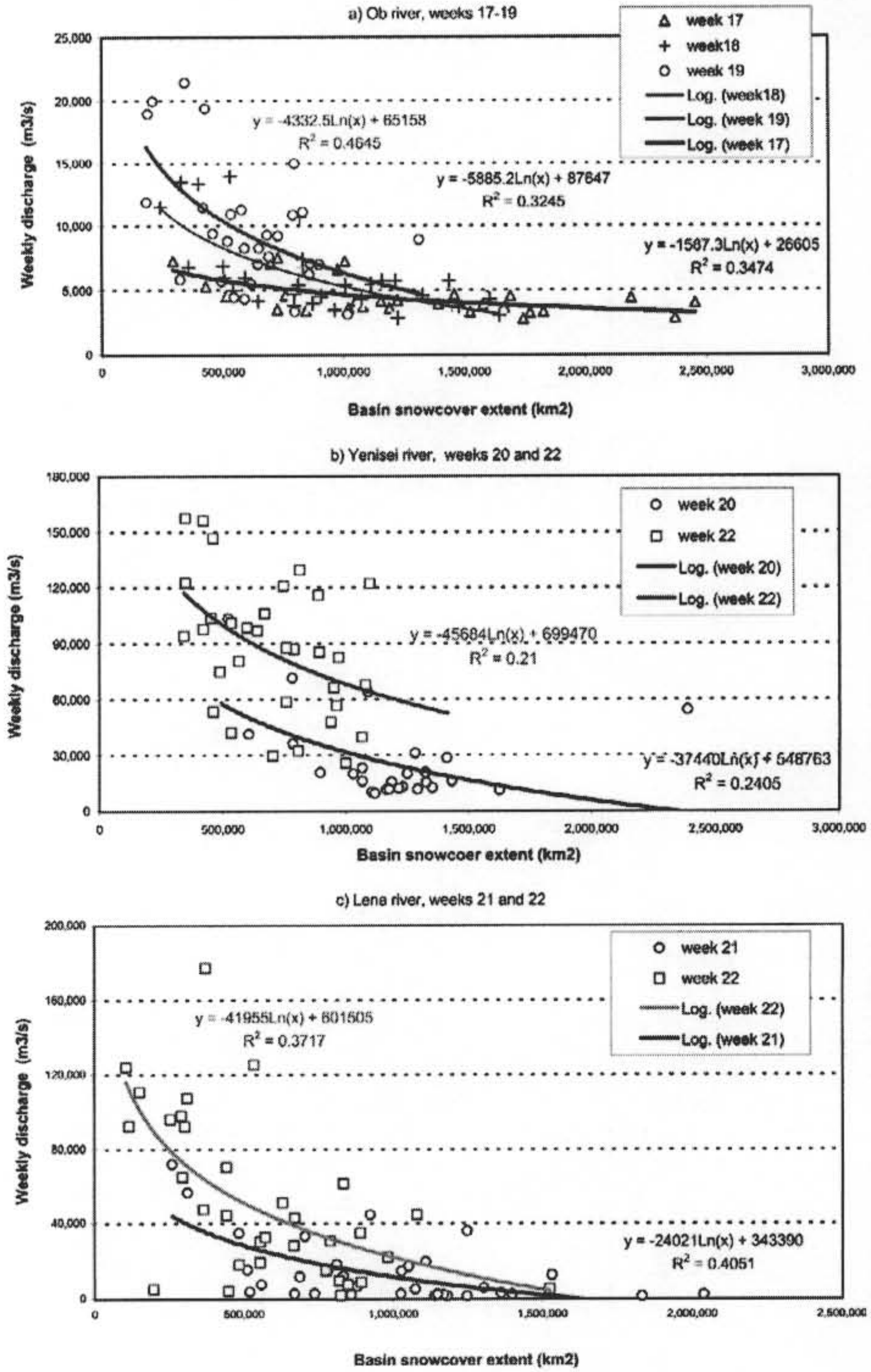

Figure 10. Regression relation between weekly discharge and basin snow cover extent during weeks of strong snowmelt. See color version of this figure in the HTML.

variability, it is necessary to examine snow cover condition and its melt processes associated with extreme runoff cases. Two example years of highest and lowest peak flows were selected for each watershed in this analysis.

[20] Discharge in spring of 1989 was very high in the Lena basin, about 170,000 m3/s, or twice the normal maximum. In this melt season, the snow cover started to melt about 2 weeks earlier than the average. The rate of melt was very high during weeks 18–20 associated with warmer temperatures in April and early May. Correspondingly, streamflow peaked earlier by about 1–2 weeks, and reached the maximum at week 22 (Figure 11a). The flow

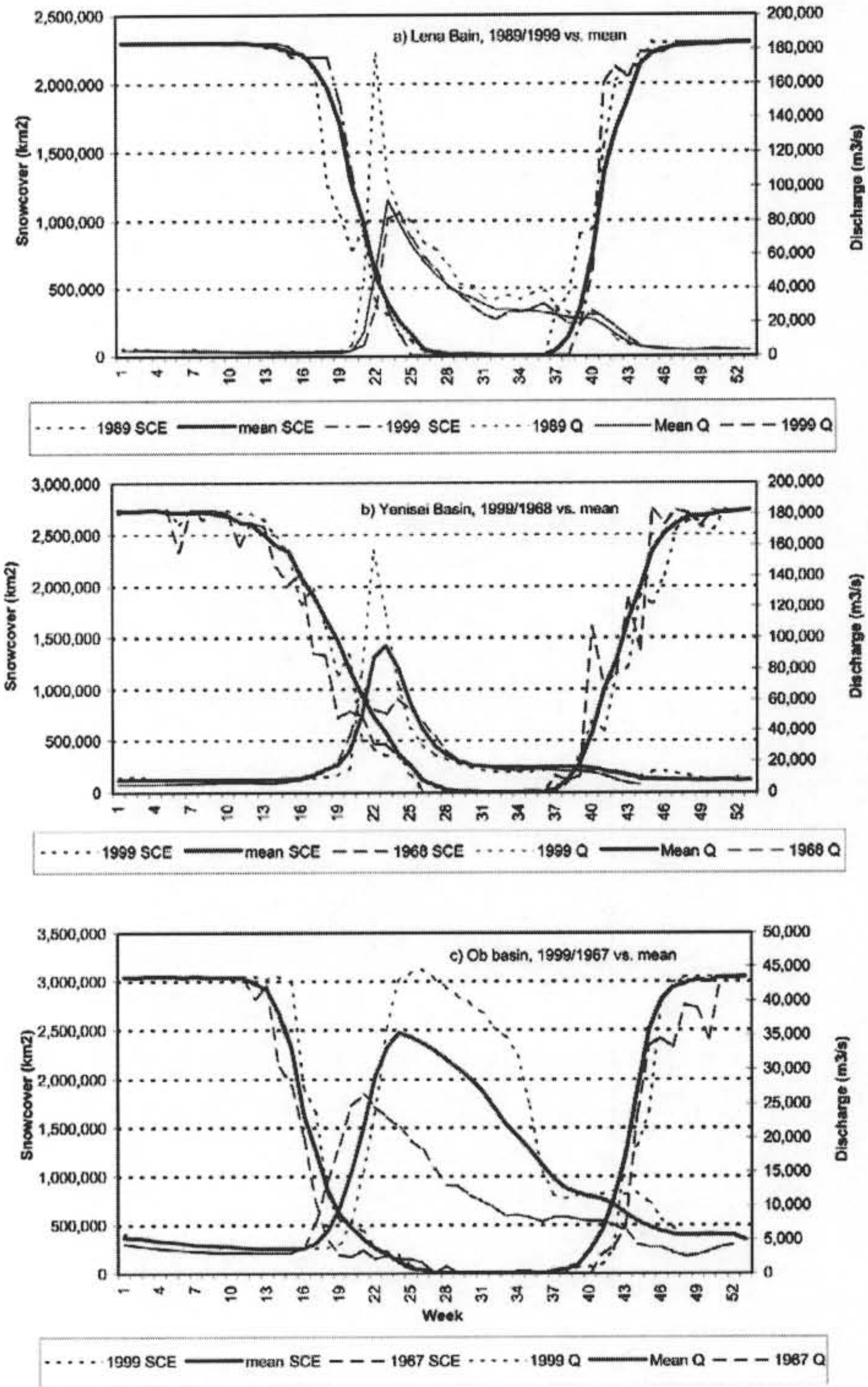

Figure 11. Comparison of extreme discharge and associated snow cover conditions over the three watersheds. See color version of this figure in the HTML.

during the postmelt weeks was also higher due to a higher winter snow accumulation. The basin mean maximum snow depth was 37.9 cm in winter of 1988/89, which is 5.5 cm higher than the long-term average snow depth of 32.4 cm [*Ye et al.*, 1998]. On the other hand, 1999 was a low runoff season in the Lena catchment. Snowmelt began late by 1–2 weeks during weeks 18–20. The rate of snow cover depletion was normal, as the temperatures in the melt season were close to average. Discharge started to rise 1 week late and peak flow was slightly lower, with the maximum (around 9000 m3/s) appearing at week 24 (Figure 11a).

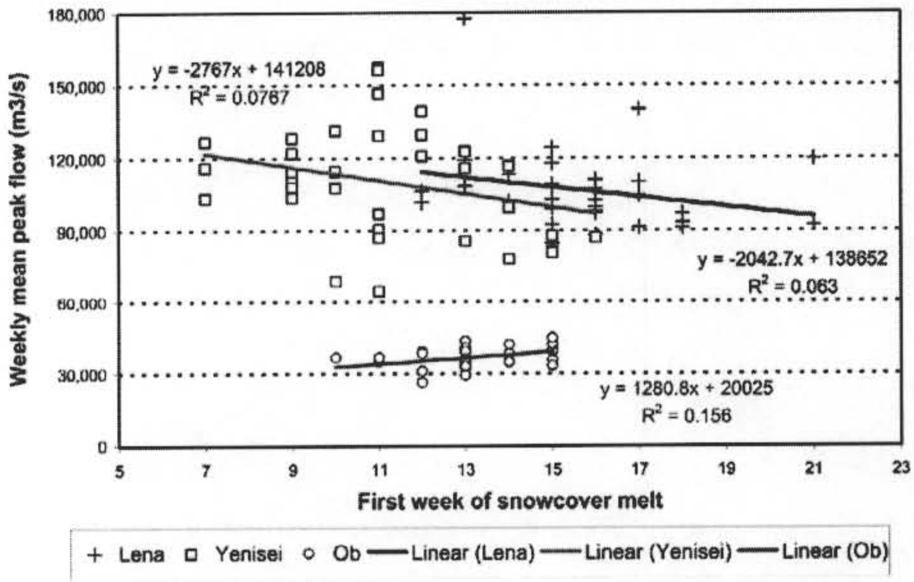

Figure 12. Scatterplots and linear regressions of weekly mean peak flow versus first week of snowmelt over the three watersheds. See color version of this figure in the HTML.

[21] The Yenisei basin had a higher flood year in 1999. Snow cover started to deplete late in this year by about 1–3 weeks, despite the higher temperatures (by 1–4°C) in April and May. This late depletion of snow cover clearly indicated a thicker snow cover over the basin that is responsible for the higher spring flood. The low peak flood in 1968 had a twin-peak feature, when the snowmelt started 1–2 weeks earlier due to high temperatures in the early spring season (Figure 11b). On the other hand, the Ob river experienced the highest peak flow in 1999 during a late snowmelt season. Spring temperatures in this year were close to normal, the slower reduction of SCE is mainly due to a thicker snowpack. The peak flow was lower in 1967 and associated with an early snowmelt season due to a warmer spring (Figure 11c), when temperatures in April and May were 5°C and 2°C higher than the long-term averages.

[22] Studies suggest that timing of the melt is important to determine the magnitude of snowmelt peak flows [*Rango*, 1996, 1997]. Field observations in northern Alaska show that an early snow cover reduction may indicate a warmer spring or a thinner snowpack, and a late melt/decline may be due to a cold spring or a thicker snow cover [*Kane et al.*, 2000]. It is important to explore and define the relationship between snowmelt timing and peak flow amount for the large Siberian rivers. To do this, we used the first week of snow cover deduction to represent the onset of snowmelt within the basins, and choose maximum weekly mean flow to reflect snowmelt runoff contribution. Comparisons of snowmelt timing with weekly mean peak flows show an association of high (low) flood peak with late (early) snowmelt in the Ob basin (Figure 12). However, the relationships are somewhat different in the Yenisei and Lena watersheds, where the high (low) flows seem to be weakly associated with early (late) snow cover melt (Figure 12). Regression analyses reveal a linear relationship (statistically significant at 95% confidence) for the Ob basin. Preliminary tests of this relation for estimating snowmelt peak flows show mixed results among the years, suggesting a need for further improvement. On the other hand, the relationships derived for the Yenisei and Lena watersheds are less significant, statistical confidence around 80–85%. The differences in the relationships of snowmelt timing versus peak discharge may indicate different responses of river peak flow to snow cover melt among western and central/eastern Siberian regions perhaps due to regional variations and differences in streamflow characteristics, and snow cover and climate conditions over Siberia. They also demonstrate the limitation of using only SCE information to examine snowmelt runoff processes over these large basins. To better understand snowmelt and runoff generation over the large northern watersheds, snow water equivalent data obtained by ground observations and remote sensing techniques are needed.

4. Conclusions

[23] This study applied remotely sensed long-term snow cover extent data in an investigation of snowmelt runoff response to seasonal snow cover change in the large Siberian watersheds. It defined the seasonal cycles and variations of snow cover extent and river streamflow, and identified a clear correspondence of river streamflow to seasonal snow cover extent change, i.e., an association of low streamflow with high snow cover extent during the cold season, and an increase in discharge associated with a decrease of snow cover during the melt periods. To quantify the relation between river runoff and basin snow cover extent variations, this study also examined and compared the weekly mean streamflow with the weekly basin snow cover extent for the study period (1966–1999). The results revealed a very strong linkage between the streamflow and snow cover extent during the spring melt season over the large Siberian watersheds, and developed a statistically significant weekly runoff-snow cover relation. It is useful

to define these relationships, as they improve our understanding of the most important Arctic hydrologic process-snowmelt peak floods, and they also suggest practical procedures of using remotely sensed snow cover information for snowmelt runoff forecasting over the large northern watersheds. Furthermore, analyses of extreme (high/low) streamflow cases (years) and the associated snow cover conditions indicate an association of high (low) flood peak with late (early) snowmelt in the Ob and Yenisei basins. Comparisons of snowmelt timing with peak flow show different associations between the two variables among the large rivers in Siberia. These results point to a need to further search for the best snowmelt-runoff relationship, and to develop the most useful snowmelt runoff forecasting methods for the large northern rivers.

[24] The results of this study demonstrate that the NOAA weekly snow cover extent data are useful for understanding and predicting streamflow changes in the Arctic regions. The methods and results of this research will be important to snowmelt model and process studies. They will improve our understanding of the spatial and temporal variability of high-latitude snow cover and its contribution to river runoff in the Arctic regions. They will also enhance our ability of modeling cold region land memory processes and predicting future changes in water cycle over large northern regions. Snow water equivalent (SWE) obtained by ground observations and remote sensing technologies is useful to better understand snowmelt runoff processes. Long-term snow water equivalent data have been derived from passive microwave sensors [*Chang et al.*, 1981; *Chang*, 1997; *Armstrong*, 1995; *Armstrong and Brodzik*, 1998, 2000]. They are potentially valuable for cold region hydrology and climate studies. Our efforts are currently underway to evaluate and use the SWE data for northern hydrology investigations.

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