h. Arctic river discharge

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The Arctic Ocean accounts for approximately 1% of the global ocean's volume but receives more than 10% of global river discharge (McClelland et al. 2012). Consequently, effects of river inputs on ocean processes are more pronounced in the Arctic and changes in river inputs have greater potential to impact ocean physics, chemistry, and biology than in other ocean basins. Because rivers naturally integrate the processes that are occurring throughout their watersheds, trends in the discharge and chemistry of Arctic rivers can also be indicative of widespread terrestrial change including permafrost thaw and the amount or seasonality of precipitation (Rawlins et al. 2010; Holmes et al. 2013).

Multiple studies over the past 20 years have demonstrated that discharge from Arctic rivers is increasing. Evidence first emerged from long-term Russian datasets (Peterson et al. 2002) and more recently from shorter U.S. and Canadian datasets (Durocher et al. 2019). While uncertainty remains around drivers of this trend, it is consistent with intensification of the Arctic hydrologic cycle (Rawlins et al. 2010). Warming is driving increased atmospheric moisture transport into the Arctic, resulting in greater precipitation (Box et al. 2019; section 5c). This is particularly evident during colder months of the year. For example, snowfall has increased during autumn and early winter in western Siberia (Wegmann et al. 2015) and in the Canadian Arctic (Kopec et al. 2016; Yu and Zhong 2021).

River discharge was last included in the *State of the Climate in 2020* report; therefore, discharge data for 2021 and 2022 are presented here. Data presentation and analysis focus on eight rivers that collectively drain much of the pan-Arctic watershed (Fig. 5.22). Six of these rivers are in Eurasia and two are in North America. Discharge measurements for the six Eurasian rivers began in 1936, whereas discharge measurements did not begin until 1973 for the Mackenzie River and 1976 for the Yukon River in North America. Years are presented as "water years", 1 October–30 September, a common practice in hydrology to align runoff and associated precipitation within the same year. Thus, water year 2022 covers the period 1 October 2021– 30 September 2022. The data used in this analysis are freely available through the Arctic Great Rivers Observatory (https://arcticgreatrivers.org/).

Fig. 5.22. Watersheds of the eight largest Arctic rivers featured in this analysis. Collectively, these rivers drain approximately 70% of the 16.8 million km^2 pan-Arctic watershed (indicated by the red boundary line). The red dots show the location of the discharge monitoring stations.

Discharge data for 2021 and 2022 are compared to a 1991–2020 reference period in this report, a change from the 1981–2010 reference period used for the previous report. Both the old and new reference periods are included in Table 5.1 to allow for continuity between reports. Combined annual discharge averaged 2397 km^3 during the new reference period and 2348 km^3 during the old reference period. While this only represents a modest 2.1% increase between the two periods, it reflects increases observed in seven out of eight individual rivers and is consistent with long-term trends of increasing Arctic river discharge.

Combined annual discharge for the eight rivers was 2555 km^3 for 2021 and 2516 km^3 for 2022 (Table 5.1). These values exceeded the 1991–2020 reference average by approximately 7% and 5%, respectively. Differences relative to the reference period were largely driven by elevated discharge in the Yukon, Mackenzie, and Yenisey Rivers, which exceeded their associated reference averages in both years. Annual discharge reached a record high in 2021 for the Yenisey. Although data accuracy for this river has declined significantly since 2003 due to a lack of rating curve updates (Tretiyakov et al. 2022), elevated values were reported across multiple gauges on the Yenisey during the summer and autumn of 2021. Annual discharge values in the Severnaya Dvina, Pechora, Ob, and Kolyma were lower than the 1991–2020 reference average in both 2021 and 2022.

Monthly data for the Eurasian rivers show that June discharge during 2021 and 2022 was well below the reference average, whereas discharge during most other months was above the reference average (Fig. 5.23a). In contrast, discharge in the North American rivers during 2021 and 2022 was above the reference average during all months (Fig. 5.23b). These results are still provisional, but patterns represented in aggregate were also evident in individual rivers. The observed increases during winter months on both sides of the Arctic are consistent with findings of other

Table 5.1. Annual discharge (km^3) for the eight largest Arctic rivers. Results are shown for 2021 and 2022 as well as mean values for old (1981–2010) and new (1991–2020) reference periods. *Italicized* values indicate provisional data and are subject to modification until official data are published.

Year[1]	Yukon (N. America)	Mackenzie (N. America)	S. Dvina (Eurasia)	Pechora (Eurasia)	Ob′ (Eurasia)	Yenisey (Eurasia)	Lena (Eurasia)	Kolyma (Eurasia)	Total
2022	*240*	*349*	*85*	*96*	*381*	*663*	*630*	*72*	*2516*
2021	*233*	*382*	*82*	*89*	*415*	*745*	*541*	*68*	*2555*
1981–2010	205	288	104	114	398	612	557	70	2348
1991–2020	*211*	*291*	*106*	*116*	*416*	*606*	*573*	*78*	*2397*

[1] Year refers to Water Year (1 October of the previous year to 30 September of the noted year)

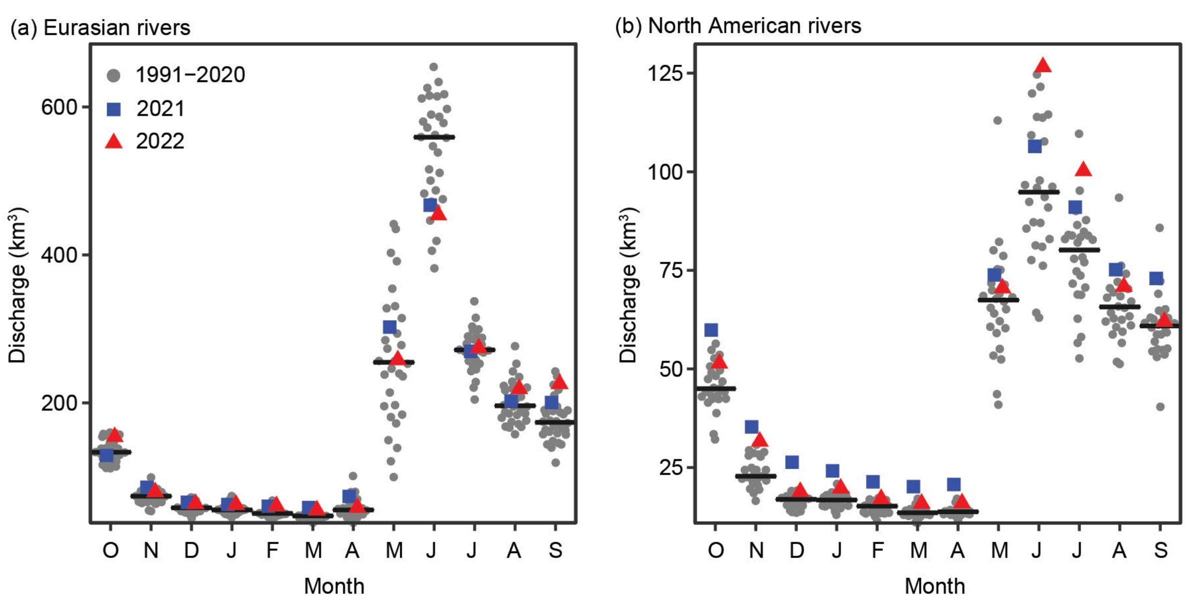

Fig. 5.23. Monthly discharge (km^3) in (a) Eurasian and (b) North American rivers for 2021 (blue squares) and 2022 (red triangles) compared to monthly discharge throughout the 1991–2020 reference period (gray circles). The black bars indicate average monthly discharge during the reference period. Note the different magnitudes of discharge between the Eurasian and North American rivers (see y-axes).

recent studies of northern rivers (Gohari et al. 2022; Whitfield et al. 2021; Hiyama et al. 2023). Widespread changes in winter discharge have been attributed to increasing baseflow as a consequence of general warming and associated permafrost degradation that supports greater groundwater contributions as well as changes in the timing and magnitude of snowmelt events (Shrestha et al. 2021; Liu et al. 2022).

The 87-year time series available for the Eurasian Arctic rivers demonstrates a continuing, and perhaps accelerating, increase in their combined discharge (Fig. 5.24a). The positive linear trend across this entire time series indicates that the average annual discharge of Eurasian Arctic rivers is increasing by 2.5 $km^3\ yr^{-1}$. When data are considered from 1976 through 2022 (the period of record for North American rivers), the average annual increase in discharge for Eurasian Arctic rivers is 4.2 $km^3\ yr^{-1}$. For the North American Arctic rivers, the average discharge increase over the period of record is 1.5 $km^3\ yr^{-1}$. These observations show that, although river discharge varies widely over interannual-to-decadal timeframes, longer-term increases in river discharge are a pan-Arctic phenomenon. Evidence of increasing Arctic river discharge is strongest for Eurasian rivers where datasets are longest, but the signal of change in North American rivers is becoming increasingly robust as discharge datasets lengthen. This serves as a reminder that maintaining long-term datasets is crucial for tracking and understanding change.

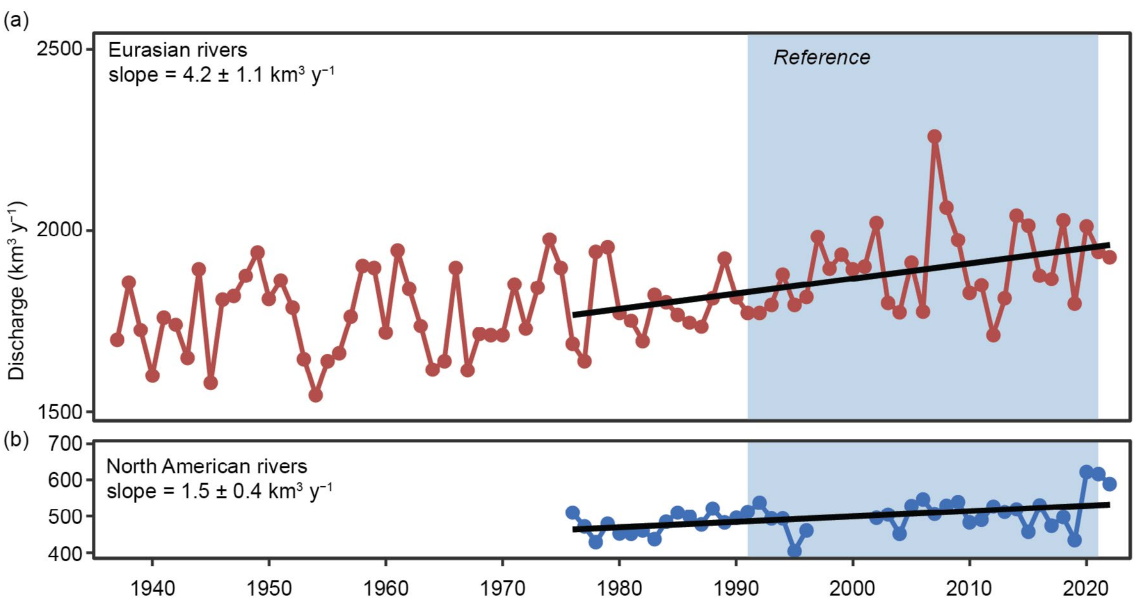

Fig. 5.24. Long-term trends in annual discharge (km^3) for (a) Eurasian and (b) North American Arctic rivers. The North American time series gap from 1996 to 2001 is due to insufficient data availability during those years. Reported slopes ($p < 0.001$ for both) are for 1976–2022.

i. Permafrost

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Permafrost refers to earth materials (e.g., bedrock, mineral soil, organic matter) that remain at or below 0°C for at least two consecutive years, although most permafrost has existed for much longer (centuries to several millennia). Overlying the permafrost is the active layer, which thaws and refreezes annually. Permafrost underlies extensive regions of the high-latitude landscape (Brown et al. 1997) and, especially if ice-rich, can play a critical role in the stability of Arctic landscapes. Warming of permafrost, active layer thickening, and ground-ice melt cause changes in surface topography, hydrology, and landscape stability, with implications for Arctic infrastructure and ecosystem integrity, as well as human livelihoods (Romanovsky et al. 2017; Hjort et al. 2022; Wolken et al. 2021). Changes in permafrost conditions can also affect the rate of greenhouse gas release to the atmosphere, with the potential to accelerate global warming (Schuur 2020).