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River Discharge: In State of the Climate in 2015.

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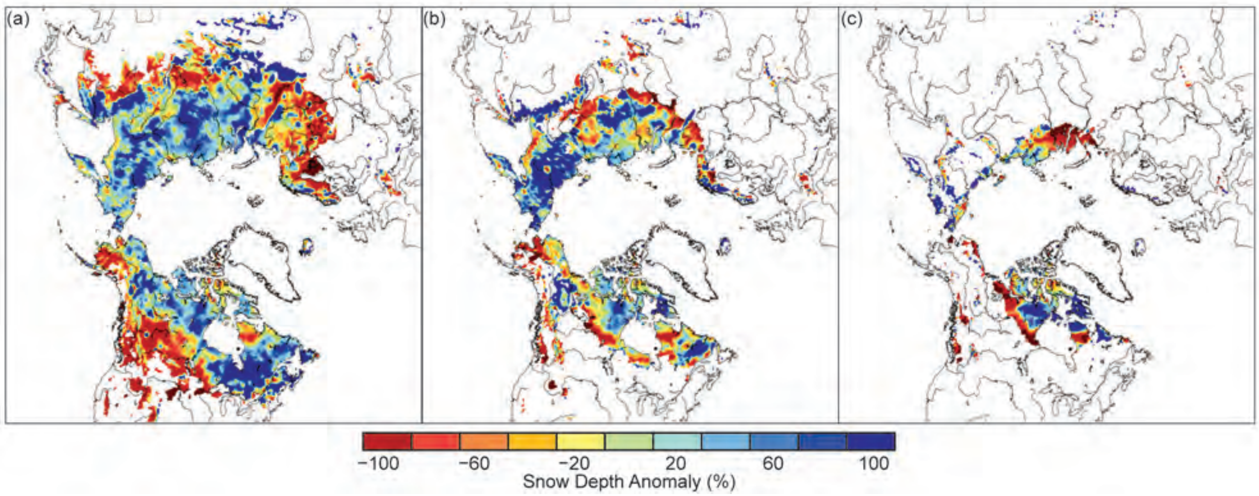

FIG. 5.17. Snow depth anomaly (% of 1999–2010 average) from the CMC snow depth analysis for (a) Apr, (b) May, and (c) Jun 2015.

h. River discharge—R. M. Holmes, A. I. Shiklomanov, S. E. Tank, J. W. McClelland, and M. Tretiakov

River discharge integrates hydrologic processes occurring throughout the surrounding landscape. Consequently, changes in the discharge of large rivers can be a sensitive indicator of widespread changes in watersheds (Rawlins et al. 2010; Holmes et al. 2013). Changes in river discharge also impact coastal and ocean chemistry, biology, and circulation. This interaction is particularly strong in the Arctic, given the relative volume of river discharge to ocean volume. Rivers in this region transport >10% of the global river discharge into the Arctic Ocean, which represents only ~1% of the global ocean volume (Aagaard and Carmack 1989; McClelland et al. 2012).

In this section, annual river discharge values since 2011 are presented for the eight largest Arctic rivers, and recent observations are compared to a 1980–89 reference period (the first decade with data from all eight rivers). Six of the rivers lie in Eurasia and two are in North America. Together, the watersheds of these rivers cover 70% of the 16.8×10^6 km^2 pan-Arctic drainage area and, as such, account for the majority of riverine freshwater inputs to the Arctic Ocean (Fig. 5.18). Discharge data for the six Eurasian rivers are analyzed through 2015, whereas data from the Yukon and Mackenzie Rivers in North America are only available through 2014. Most of these data are now available through the Arctic Great Rivers Observatory (www.arcticgreatrivers.org).

A long-term increase in Arctic river discharge has been well documented and may be linked to increasing precipitation associated with global warming (Peterson et al. 2002; McClelland et al. 2006; Shiklomanov and Lammers 2009; Overeem and Syvitski 2010; Rawlins et al. 2010). The long-term discharge trend is greatest for rivers of the Eurasian Arctic and constitutes the strongest evidence of intensification of the Arctic freshwater cycle (Rawlins et al. 2010).

In 2015, the combined discharge of 2051 km^3 for the six largest Eurasian Arctic rivers was 15% greater than the 1980–89 average (Fig. 5.19; Table 5.2), and the peak discharge occurred earlier than the average over the same period (Fig. 5.20). This is the fourth highest combined discharge value since measurements began in 1936. The four highest values have

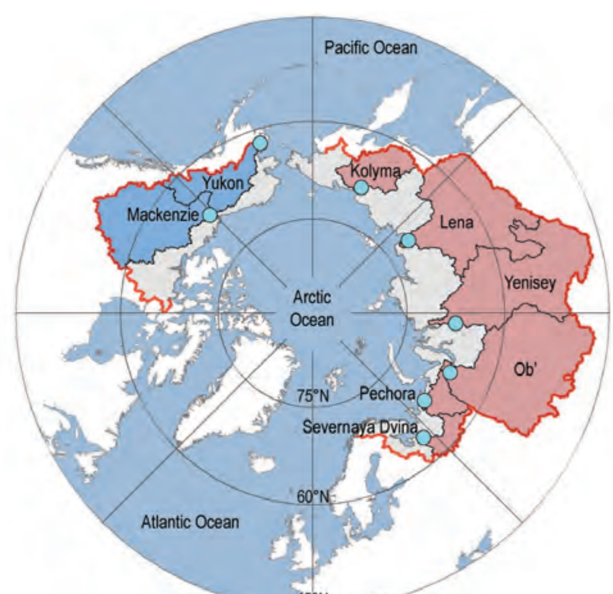

FIG. 5.18. Map showing the watersheds of the eight rivers featured in this section. The blue dots show the location of the discharge monitoring stations and the red line shows the boundary of the pan-Arctic watershed.

Table 5.2. Annual discharge for 2012, 2013, and 2014 for the eight largest Arctic rivers, compared to long-term and decadal averages back to the start of observations. Values for 2015 are provided for the six Eurasian rivers. Red values indicate provisional data, which are subject to modification before official data are released.

Discharge ($km^3\ yr^{-1}$)									
	Yukon	Mackenzie	Pechora	S. Dvina	Ob'	Yenisey	Lena	Kolyma	Sum
2015			123	80	527	654	585	82	
2014	227	272	116	91	448	640	607	86	2487
2013	213	311	82	97	372	527	600	80	2282
2012	232	306	103	117	300	458	665	59	2240
Average 2010–15	212	293	108	93	409	594	583	75	2366
Average 2000–09	207	305	124	103	415	640	603	78	2475
Average 1990–99	217	275	117	111	405	613	532	68	2338
Average 1980–89	206	273	108	100	376	582	549	68	2262
Average 1970–79	184	292	108	94	441	591	529	65	2304
Average 1960–69		273	112	98	376	546	535	73	
Average 1950–59			110	108	380	566	511	74	
Average 1940–49			102	100	424	578	498	72	
Average for Period of Record	206	286	111	100	401	589	540	71	2305

all occurred in the past 14 years. Overall, the most recent data indicate a continuing long-term increase in Eurasian Arctic river discharge, at a rate of 3.5% ± 2.1% decade^{-1} since 1976. Looking more closely at recent years, Eurasian Arctic river discharge generally declined between 2007 and 2012 and then began to increase again in 2013. Values for 2012 (1702 km^3), 2013 (1759 km^3), and 2014 (1989 km^3) were 5% less, 1% less, and 2% greater than the 1980–89 period, respectively. The short-term variability in Eurasian Arctic river discharge is consistent with previous increases and decreases over 4–6 year intervals in the past (Fig. 5.19).

For the North American Arctic rivers considered here (Yukon and Mackenzie), the combined discharge declined each year from 2012 (538 km^3) to 2014 (499 km^3), yet in each of those years the combined discharge was greater than the long-term average (493 km^3 year^{-1}; Fig. 5.19; Table 5.2). Thus, as discussed for Eurasian rivers, these most recent data indicate a longer-term pattern of increasing river discharge (Fig. 5.19). At a rate of 2.6% ± 1.7% decade^{-1} since 1976, the overall trends of increasing discharge are remarkably similar for the North American and Eurasian rivers. (Increases per decade follow a Mann – Kendall trend analysis; error bounds are 95% confidence intervals for the trend.)

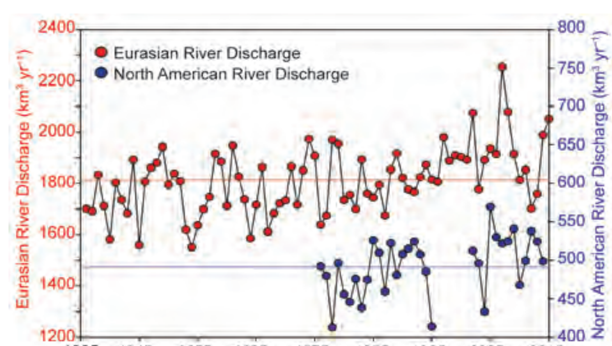

Fig. 5.19. Long-term trends in annual discharge for Eurasian and North American Arctic rivers. The Eurasian rivers are Severnaya Dvina, Pechora, Ob', Yenisey, Lena, and Kolyma. The North American rivers are Yukon and Mackenzie. Note the different scales for the Eurasian and North American river discharge; discharge from the former is 3–4 times greater than the latter. Reference lines show long-term means for the Eurasian (1812 $km^3\ yr^{-1}$, 1936–2015) and North American (493 $km^3\ yr^{-1}$, 1976–2014) rivers.

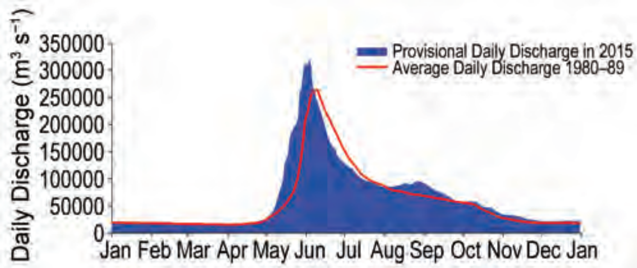

Fig. 5.20. Combined daily discharge for the six Eurasian Arctic rivers in 2015 compared to the 1980–89 average.

Considering the eight Eurasian and North American Arctic rivers together, their combined discharge in 2014 (2487 km^3) was 10% greater than the average discharge for 1980–89. Comparing 2014 to 2012, the combined discharge of these eight rivers was almost 250 km^3 greater in 2014. For perspective, 250 km^3 is approximately 14 times the annual discharge of the Hudson River, the largest river on the east coast of the United States.

i. *Terrestrial permafrost*—V. E. Romanovsky, S. L. Smith, K. Isaksen, N. I. Shiklomanov, D. A. Streletskiy, A. L. Kholodov, H. H. Christiansen, D. S. Drozdov, G. V. Malkova, and S. S. Marchenko

Permafrost is defined as soil, rock, and any other subsurface earth material that exists at or below 0°C continuously for two or more consecutive years. On top of permafrost is the active layer, which thaws during the summer and freezes again the following winter. The mean annual temperature of permafrost and the active layer thickness (ALT) are good indicators of changing climate and therefore designated as essential climate variables (Smith and Brown 2009; Biskaborn et al. 2015) by the Global Climate Observing System Program of the World Meteorological Organization. Changes in permafrost temperatures and ALT at undisturbed locations in Alaska, Canada, Russia, and the Nordic region (Fig. 5.21) are reported here. Regional variability in permafrost temperature records, described below, indicates more substantial permafrost warming since 2000 in higher latitudes than in the subarctic. This is in general agreement with the pattern of average air temperature anomalies.

In 2015, record high temperatures at 20-m depth were measured at all permafrost observatories on the North Slope of Alaska (Barrow, West Dock, Franklin Bluffs, Happy Valley, and Galbraith Lake in Fig. 5.22a; Romanovsky et al. 2015). The permafrost temperature increase in 2015 was substantial and comparable to the highest rate of warming observed in this region so far, which occurred during the period 1995–2000; 20-m depth temperatures in 2015 were from 0.10°C to 0.17°C higher than those in 2014 (Fig. 5.22a) on the North Slope. Since 2000, temperature at 20-m depth in this region has increased between 0.21°C and 0.66°C decade^{-1} (Fig. 5.22a; Table 5.3). Permafrost temperatures in Interior Alaska were higher in 2015 than 2014 at all sites (Old Man, College Peat, Birch Lake, Gulkana, and Healy in Fig. 5.22b), except for Coldfoot. Notably, this warming followed slight cooling of 2007–13 (Fig. 5.22b). However, the recent warming in the interior (see section 5b; Fig. 5.2) was not strong enough to bring permafrost temperatures back to the record highs observed between the mid-1990s and the mid-2000s except at Gulkana (Fig. 5.22b; Table 5.3).

In northwestern Canada, temperatures in warm permafrost of the central Mackenzie Valley (Norman Wells and Wrigley in Fig. 5.22b) were similar in 2014/15 to those observed the previous year.

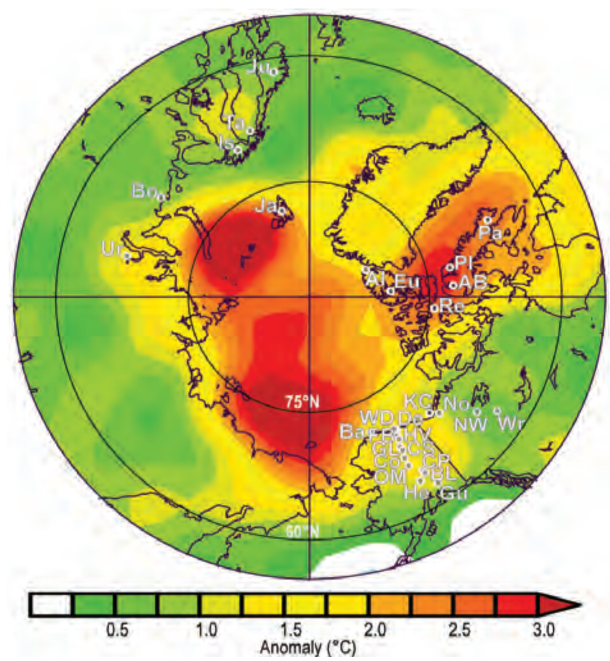

Fig. 5.21. Location of the permafrost monitoring sites shown in Fig. 5.22 superimposed on average air temperature anomalies during 2000–14 (with respect to the 1971–2000 mean) from the NCEP–NCAR reanalysis (Kalnay et al. 1996) (Source: NOAA/ESRL.) Sites shown in Fig. 5.22 are (a) Barrow (Ba), West Dock (WD), KC-07 (KC), Deadhorse (De), Franklin Bluffs (FB), Galbraith Lake (GL), Happy Valley (HV), Norris Ck (No); (b) College Peat (CP), Old Man (OM), Chandalar Shelf (CS), Birch Lake (BL), Coldfoot (Co), Norman Wells (NW), Wrigley 2 (Wr), Healy (He), Gulakana (Gu), Wrigley 1 (Wr); (c) Eureka EUK4 (Eu), Alert BH2 (Al), Alert BH5 (Al), Resolute (Re), Alert BH1 (Al), Arctic Bay (AB), Pond Inlet (PI), Pangnirtung (Pa); (d) Janssonhaugen (Ja), Urengoy #15-10 (Ur), Juvvasshøe (Ju), Tarfalaryggen (Ta), Bolvansky #59 (Bo), Bolvansky #65 (Bo), Urengoy #15-06 (Ur), Bolvansky #56 (Bo), Iskoras Is-B-2 (Is).