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Diagnosis of the record discharge of Arctic-draining Eurasian rivers in 2007

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Abstract

Aggregate annual discharge from the six largest Arctic-draining Eurasian rivers achieved an all-time record high in 2007, accentuating a long-term upward trend that argues for intensification of the Arctic hydrologic cycle. This record discharge was due in part to strong positive anomalies in late winter snow water equivalent across much of northern Eurasia. These anomalies arose in response to an unusual pattern of atmospheric circulation in late 2006 and early 2007, characterized by an extreme northeastward extension of the Icelandic Low and a contraction of the Siberian High. Positive net precipitation anomalies then continued into summer, further contributing to discharge.

Keywords: SWE, river discharge, NAO, atmospheric circulation

1. Introduction

Research programs such as the National Science Foundation Freshwater Integration (FWI) have brought a wealth of knowledge regarding the Arctic's large-scale freshwater budget (Serreze *et al* 2006), linkages between land–surface hydrology and nutrient fluxes (McClelland *et al* 2007, Frey *et al* 2003), the dynamics of freshwater transfer between the atmosphere, river systems and Arctic Ocean (Rawlins *et al* 2009a), and anticipated changes in the water cycle through the 21st century (Holland *et al* 2007). Simulations from global coupled climate models with rising atmospheric greenhouse gas concentrations consistently point to intensification of the Arctic's hydrologic cycle, with increased precipitation, evaporation and annual river discharge (Wu *et al* 2005, Holland *et al* 2006, Kattsov *et al* 2007). Observed increases in annual discharge aggregated for the six largest Eurasian rivers (Peterson *et al* 2002, Richter-Menge *et al* 2006), daily minimum flows from small-to medium-sized Eurasian rivers (Smith *et al* 2007) and solid precipitation measured throughout the region (Ye *et al* 1998, Frey and Smith 2003, Rawlins *et al* 2009b) are broadly consistent with these projections. These hydrologic trends are components of a larger picture of Arctic change over recent decades (Serreze *et al* 2003b, ACIA 2005, White *et al* 2007) that includes a strong downward trend in summer Arctic sea ice extent (Stroeve *et al* 2007, Comiso *et al* 2008), particularly along the Russian shelves (Mahoney *et al* 2006), warming and thawing of permafrost (Osterkamp 2005, Romanovsky *et al* 2007), and rises in surface air temperature (Serreze *et al* 2009).

Discharge records for Arctic-draining Eurasian rivers span 70+ years. Combined annual discharge from the six largest river basins in Eurasia (from west to east: Severnaya Dvina, Pechora, Ob, Yenisei, Lena, Kolyma) reached an historical high of 2254 $\mathrm{km^3\ yr^{-1}}$ in 2007, 25% above the long-term mean of 1796 $\mathrm{km^3\ yr^{-1}}$ (figure 1, Shiklomanov and Lammers 2009), serving as an exclamation point on the long-term upward trend. Individually, the Yenisei and Pechora basins experienced record high flows in 2007. The present study examines processes leading to this record aggregate discharge using various fields from the National Centers for Environmental Prediction/National Center for Atmospheric

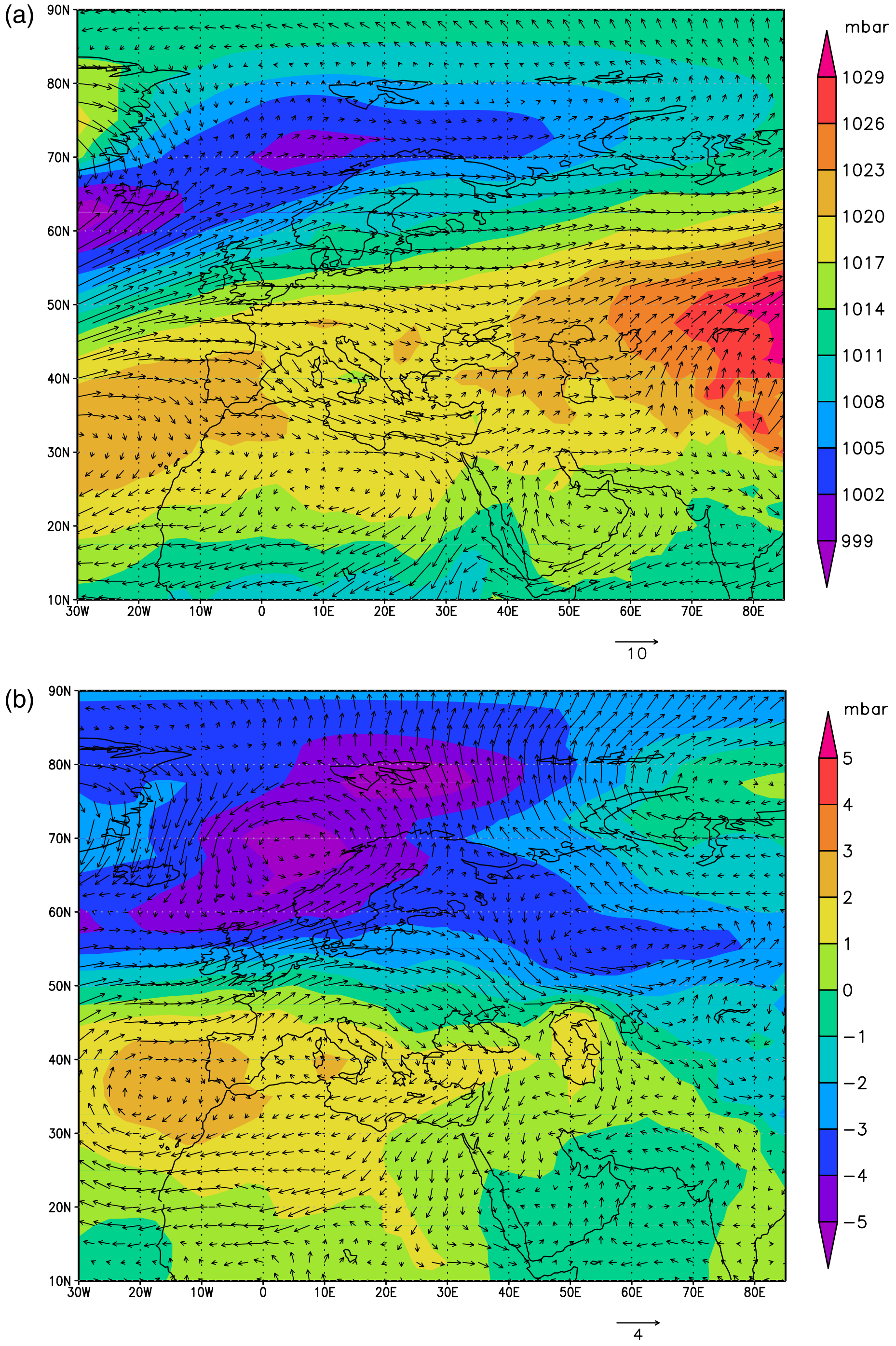

Figure 1. (a) Mean November–March sea level pressure (SLP) and 850 hPa winds from the NCEP/NCAR reanalysis averaged over the period 1980–2007 and (b) anomalies in SLP and 850 hPa winds for November–March 2006/2007, relative to 1980–2007 means.

Research (NCEP/NCAR) atmospheric reanalysis and output from a hydrological model.

2. Data

Sea level pressure (SLP) and 850 hPa winds from the NCEP/NCAR reanalysis (Kalnay *et al* 1996) (http://www.cdc.noaa.gov/) were obtained for the period 1980–2007. NCEP/NCAR fields are available from 1948 onwards but those for the period since 1979, which incorporate modern satellite data streams, are of higher quality. NCEP/NCAR data were also used to compute monthly fields of precipitation minus evapotranspiration ($P - E$) for the same period via the aerological method, in which the vertically integrated vapor flux convergence is adjusted by the time change in precipitable water (Serreze *et al* 2002). We make use of fields of $P - E$ interpolated to a 25 km resolution equal-area scalable grid (EASE Grid) for the pan-Arctic terrestrial drainage basin that are available as part of the Arctic-RIMS archive (http://rims.unh.edu/).

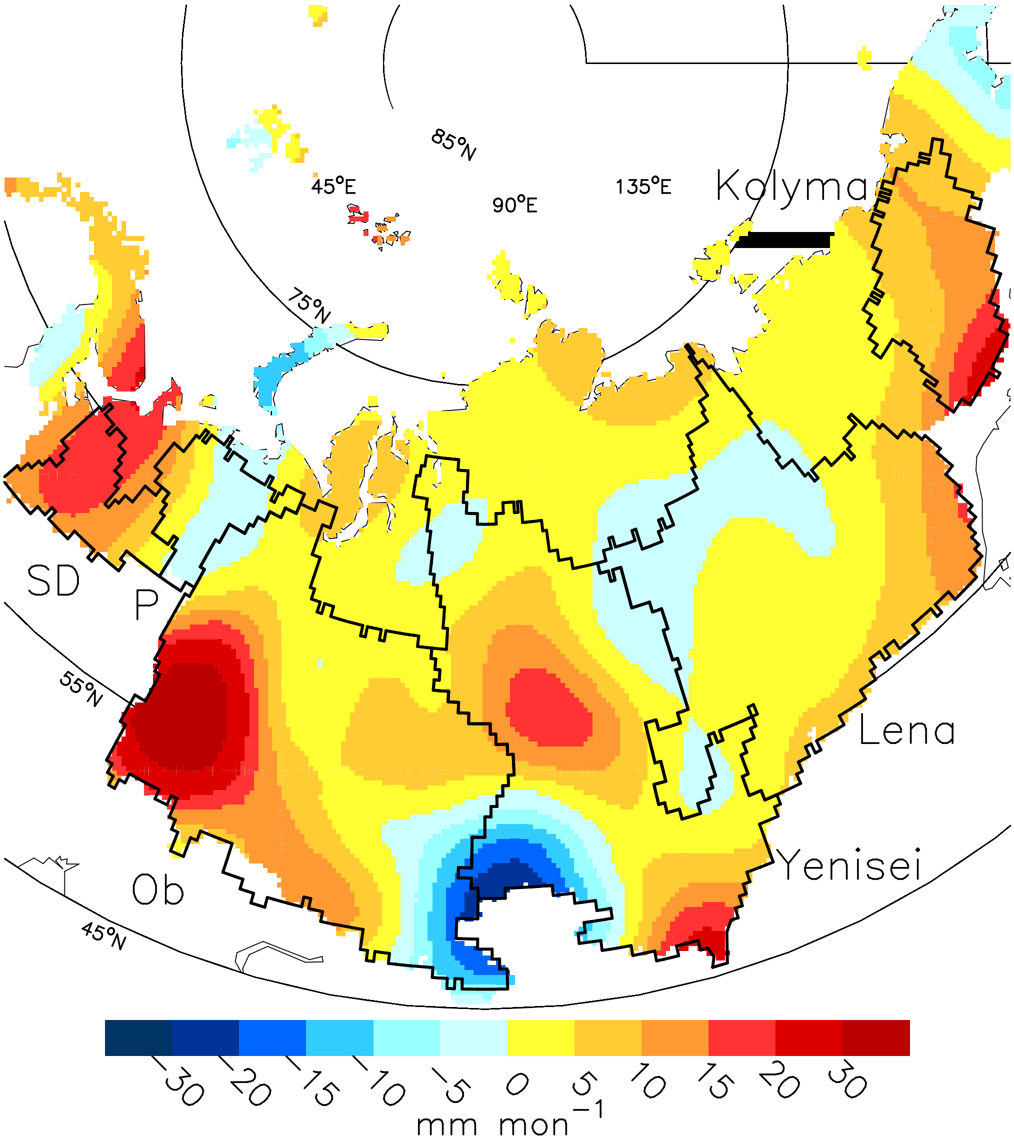

Figure 2. Anomalies in mean November–March 2006/2007 aerological net precipitation ($P - E$) from NCEP/NCAR data. The $P - E$ fields are shown for all 25 km EASE grid cells of the Eurasian Arctic drainage basin. River basins outlined from west to east are the Severnaya Dvina, Pechora, Ob, Yenisei, Lena and Kolyma. Anomalies are determined with respect to the period 1980–2007.

Seasonal water storage as snow water equivalent (SWE) is a major driver of high-latitude river flows (Serreze *et al* 2002). Fields of SWE for 1980–2007 were obtained from a simulation with the Pan-Arctic Water Balance Model (PWBM) (Rawlins *et al* 2003). PWBM is forced with daily gridded air temperature and precipitation data from Arctic-RIMS, also based on NCEP/NCAR fields. The daily precipitation product combines de-biased precipitation forecasts from NCEP/NCAR and other predictors in a multiple linear regression approach. The simulated snowpack contains both a solid (frozen) and a liquid portion, with the latter retained within the snowpack if present. The sum of both amounts constitutes the SWE estimate. SWE fields from PWBM compare favorably to estimates from land–surface models and remote sensing data (Rawlins *et al* 2007).

Assessments of atmospheric linkages also make use of indices of the North Atlantic Oscillation (NAO), a major mode of atmospheric variability in the Northern Hemisphere representing co-variability in the strengths of the Icelandic Low and Azores High (Jones *et al* 1997) (http://www.cru.uea.ac.uk/~timo/projpages/nao_update.htm) and the Arctic Rapid Change Pattern (ARP), which was introduced recently in a study by Zhang *et al* (2008).

3. Diagnosis of record 2007 discharge

Seasonal snowmelt produces a pronounced peak in discharge of these large Eurasian rivers around June. Figure 1 provides insights into the origin of the positive SWE anomalies that contributed to the record river discharge. The two map panels show, respectively, the mean November–March SLP and wind field at 850 hPa (averaged over the period 1980–2007) and anomalies for November–March 2006/2007. The mean November–March SLP pattern (figure 1(a)) features low

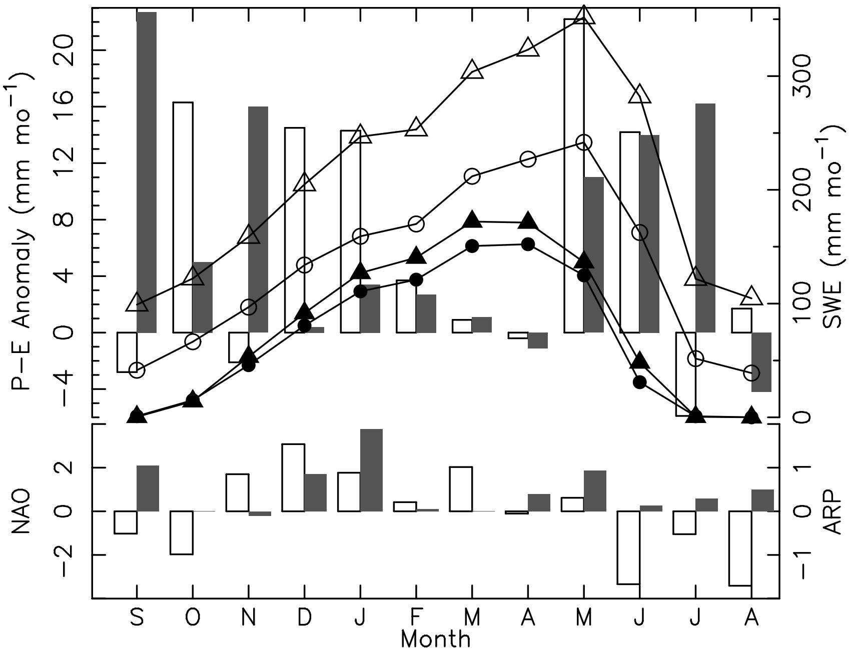

Figure 3. (Upper) Net precipitation ($P - E$) anomaly (relative to 1980–2007 means) averaged across the western and central river basins (Severnaya Dvina, Pechora, Ob, Yenisei; open bars) and eastern basins (Lena and Kolyma; gray bars) (mm mo^{-1}); snow water equivalent (SWE) averaged across all six basins, 1980–2007 (filled circles); SWE in 2006/2007 (filled triangles), SWE (1980–2007) averaged across grid cells outside of the six Eurasian basins (section 2) north of 50°N and between 40°E and 160°E (open circles); and SWE during 2006/2007 across the same areas (open triangles). These areas can also be seen in figure 4. (Lower) North Atlantic Oscillation (NAO, open bars) and Arctic Rapid Change Patten (ARP, gray bars) Indexes for the months of September 2006 to August 2007.

pressure centered near Iceland (the Icelandic Low) and high pressure over central Eurasia (part of the Siberian High). Recent winters have seen a pronounced shift to the positive phase of ARP just mentioned (Zhang *et al* 2008). This is manifested in the November 2006 to March 2007 SLP anomaly field in the northeastward extension of the Icelandic Low, contraction of the Siberian High and an enhanced wind flow at 850 hPa from moisture sources in the North Atlantic into western Eurasia (figure 1(b)). The deeper Icelandic Low during November–March 2006/2007 is also reflected in the positive phase of the NAO, which is known to promote increased moisture transport into the Arctic Basin during winter (Dickson *et al* 2000).

Attendant $P - E$ anomalies are positive over much of the Eurasian Arctic drainage basin (figure 2). $P - E$ anomalies are particularly strong and positive over the western Ob basin (locally exceeding 20 mm mo^{-1}), which can be linked to the anomalous airflow and implied moisture transport just mentioned. The positive anomalies are greatest over the western Ob basin, specifically across the Irtish basin which accounts for 22% of the flow from the entire Ob watershed. Reasons for the appearance of negative $P - E$ anomalies over central Eurasia, where SLP anomalies are also negative, are unclear. Drawbacks with the aerological $P - E$ method include problems with poor instrument performance at low temperatures, differences in rawinsonde type and reporting practices, and shortcomings in data assimilation methods (Cullather *et al* 2000, Serreze *et al* 2003a). There is a region of strongly negative $P - E$ anomalies straddling the southern reaches of the Ob and Yenisei basins. Monthly $P - E$ anomalies averaged across the western and central basins (the Pechora, Severnaya Dvina, Ob and Yenisei) and the eastern ones (Lena and Kolyma) are shown in figure 3. Positive $P - E$ anomalies dominate the period between September 2006 and August 2007. They are also greater across western Eurasia during the cold season from October 2006 through May 2007. Positive $P - E$ anomalies from September 2006 to January 2007, and during May–July 2007, range from 37 and 65% of the long-term mean, as compared to the 2007 river discharge anomaly that was ~25% above the long-term mean. Between November and March the NAO index was consistently positive (meaning a strong Icelandic Low), with the ARP index positive during December and January. The NAO November–March index average for 2006/2007 was higher than for any other winter since 1994/1995 (http://www.cru.uea.ac.uk/~timo/projpages/nao_update.htm).

The positive anomalies in winter $P - E$ depicted in figures 2 and 3 will be expressed in SWE. Late winter (February–March) SWE anomalies are largest across western Eurasia, including the northern half of the Ob basin, and locally exceed 100 mm mo^{-1} (figure 4). Anomalies are also positive over much of the Yenisei and Lena basins. Consistent with the pattern of $P-E$ anomalies, partly compensating negative SWE anomalies are most pronounced across the extreme southern reaches of the Ob basin. Averaged over the six Eurasian basins, monthly SWE exceeds the 1980–2007 mean each month from September 2006 into summer 2007, with the anomaly reaching a maximum in March (figure 3). Monthly SWE anomalies are particularly large for the largely ungauged region north of the six basins.

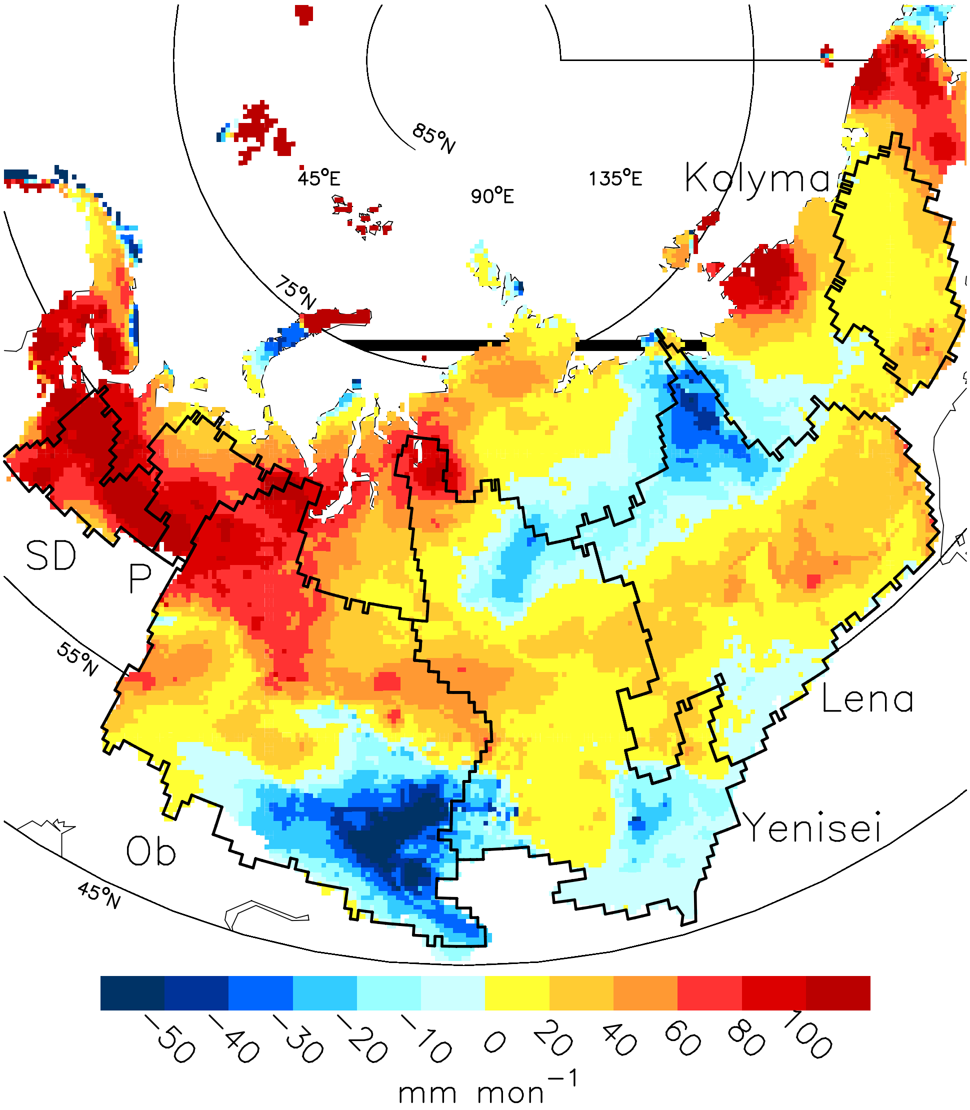

Figure 4. Anomalies in mean late winter (February–March) 2007 SWE (mm mo^{-1}) based on simulations with the Pan-Arctic Water Balance Model (Rawlins *et al* 2003). Anomalies are with respect to the period 1980–2007.

Over the 1980–2007 period, the six-basin-average SWE anomaly in late winter 2007 ($\sim$20 mm mo^{-1}) was the third most positive among all years, exceeded only by 1997 and 1999 (figure 5). While of course consistent with high discharge, figure 3 indicates that an additional key contributor to the record flow was the persistence of positive $P - E$ anomalies through summer. The combination of high winter SWE and positive $P - E$ anomalies in June and July in turn explains the abundance of inundated areas across the Ob basin during late spring and early summer (Schroeder *et al* 2009).

Also of note in figure 5 is the significant positive linear trend ($p < 0.02$) in SWE. This trend drawn from model-simulated SWE across the six largest Eurasian basins is consistent in sign with the reported positive trends in winter precipitation over the latter decades of the 20th century (Frey and Smith 2003, Rawlins *et al* 2009b) and river discharge from 1936–2007 (Shiklomanov and Lammers 2009).

4. Summary and discussion

Anomalous $P - E$ during November–March of 2006/2007 linked to the record aggregate discharge was associated with an anomalous circulation pattern featuring low pressure extending eastward into western and central Eurasia, linked in turn to positive phases of the NAO and ARP. The anomalous winter $P - E$ pattern was manifested as positive SWE anomalies, particularly across western Eurasia, during winter. Translation of the Icelandic Low northeastward in recent decades associated with the changing phase of the ARP has also been cited as a significant driving factor for changes in Arctic sea ice extent, surface air temperatures and poleward heat transport (Zhang *et al* 2008). Annual discharge was further boosted by positive $P - E$ anomalies through summer.

Interestingly, these moist summer conditions can be linked to persistent low pressure over central and western Siberia, a pattern which, combined with summer anticyclonic conditions over the central Arctic Ocean, led to a wind field known to

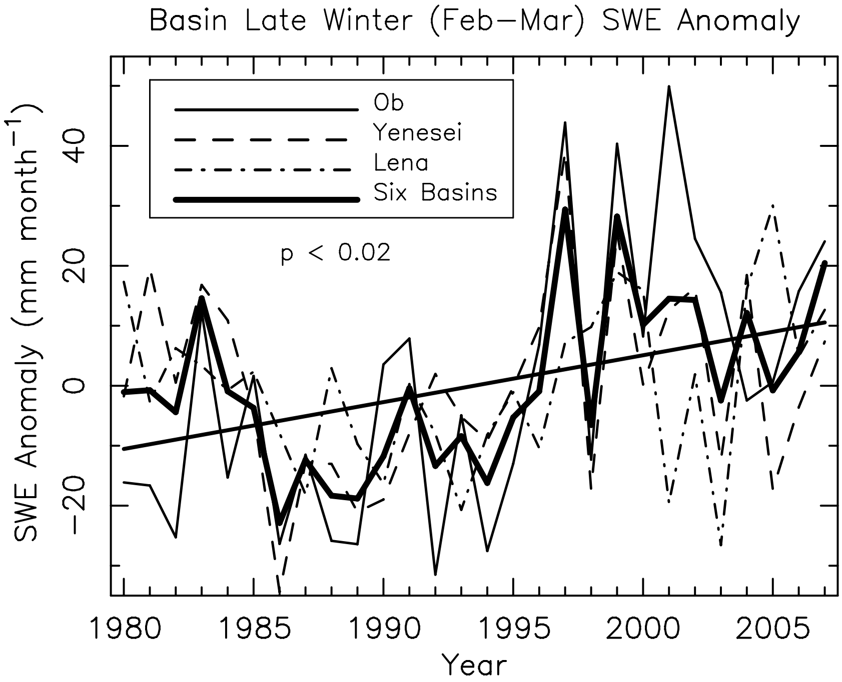

Figure 5. Basin averaged anomalies in late winter (February–March) SWE (mm mo^{-1}) averaged for the Ob, Yenisei, Lena and all six Eurasian basins over the period 1980–2007. The linear least-squares fit to six-basin-average SWE is also shown.

have been a strong driver of the record low sea ice extent of September 2007 (Stroeve *et al* 2007). That strong positive late winter SWE anomalies were found north of the Ob, Yenisei and Lena basins in the largely ungauged portion of the Eurasian drainage furthermore implies that freshwater flows onto the Russian coastal shelves were greater than assessed from flows of the large rivers. A question that naturally arises is how this strong pulse of fresh water to the coastal shelves influenced autumn sea ice growth. This could be addressed via experiments with coupled ice–ocean models incorporating observed river discharge.

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