1 Meteorology

Figure S1: Mean-monthly climatology of meteorological variables in each driving data set, averaged over the common overlap period, 2002–2010. (a) Precipitation (mm d^{-1}), (b) Near surface air temperature (K), (c) Specific humidity (g kg^{-1}), (d) Wind speed at 10 m (m s^{-1}). Error bars show the standard deviation. The precipitation differs significantly between the data sets with and without undercatch correction. In general, the air temperature is very similar between data sets, except in the Mackenzie. The specific humidity is much higher in the PGF data than in the other data sets. The wind speed is variable between data sets in all basins.
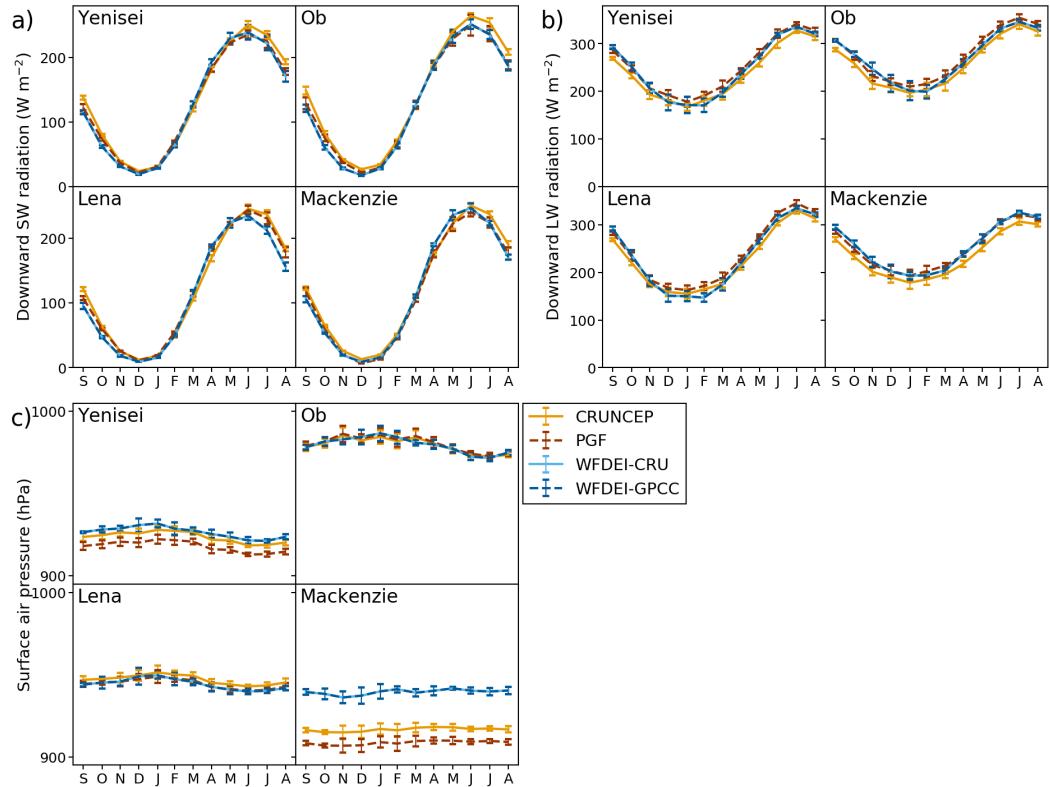
Figure S2: Mean-monthly climatology of meteorological variables in each driving data set, averaged over the common overlap period, 2002–2010. (a) Downward shortwave radiation (W m^{-2}), (b) Downward longwave radiation (W m^{-2}), (c) Surface air pressure (hPa). Error bars show the standard deviation. The radiation variables are both quite consistent between data sets. The surface air pressure is most variable in the Mackenzie and the Yenisei, and more consistent in the Lena and Ob.

2 Precipitation
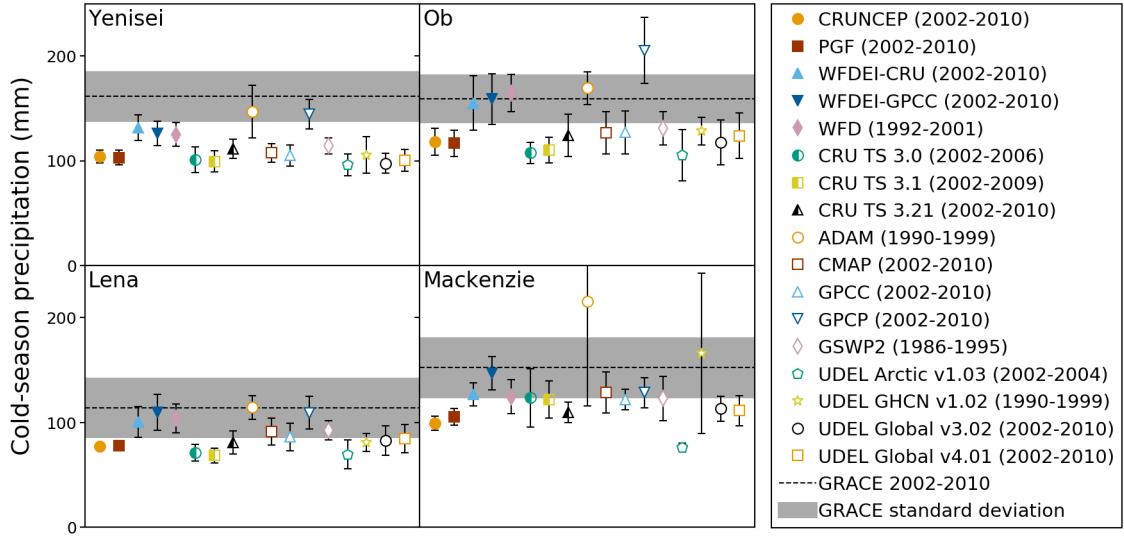
Figure S3: Mean cold season (October – February) precipitation calculated from several gridded, observation-based data sets. Where the data are available, the means are calculated over the nine-year common overlap period used in this study, 2002–2010. If the data partially overlap with this period, then the years of overlap are used. Otherwise, the last nine years of the data set are used. Years used for each data set are noted in the legend. The first four data sets are the driving data used in this study [1, 2, 3], the fifth, WFD [4], is the precursor to the WFDEI data sets. The next three are three different versions of CRU TS [5]. Two of these (3.1 and 3.21) have been used in bias-correcting the driving data used in this study. The rest are precipitation data from a variety of sources (ADAM [6], CMAP [7, 8], GPCC v7 [9, 10], GPCP v2.2 [11], GSWP2 [12], UDEL [13, 14, 15, 16]). Earlier versions (v5 and v6) of the GPCC data set were used to bias-correct the WFDEI-GPCC driving data. The black dashed line shows the mean cold season precipitation calculated using the GRACE-based water balance (Section 4.1), with the shaded grey area showing the standard deviation. In general, most of the data sets lie below the GRACE estimate. Some, notably the WFDEI driving data, which include undercatch correction, are much closer to the GRACE mean, but still tend to underestimate overall, while a few significantly overestimate.

3 Basin fluxes
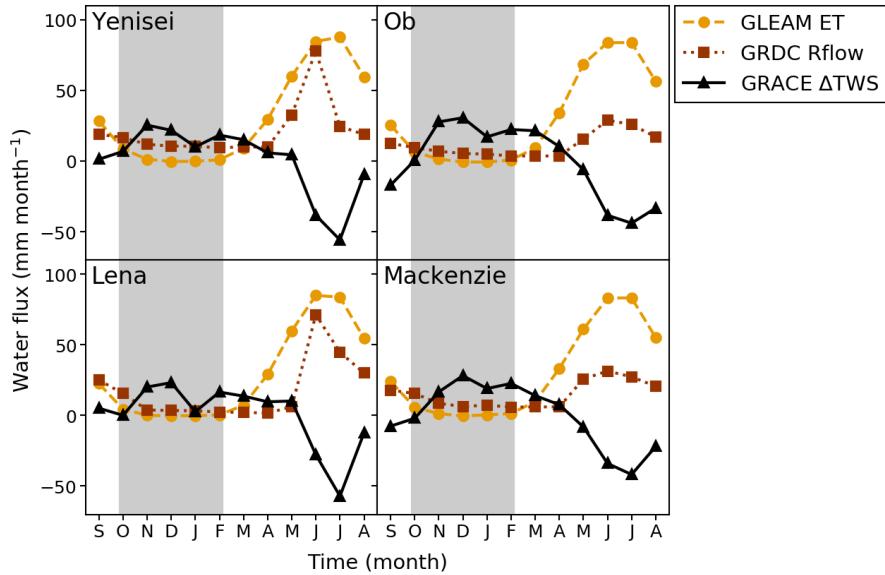
Figure S4: Mean-monthly climatology of the fluxes used to calculate the inferred precipitation (GLEAM evapotranspiration, GRDC basin discharge and change in GRACE total water storage (TWS) for the common overlap period, 2002–2010. The grey shaded area shows the months (October – February inclusive) which are considered when calculating the cold season precipitation. In these months the relative sizes of the evaporation and basin discharge are similar to or smaller than the change in TWS estimated by GRACE. Outside of these months, the calculation is dominated by the evaporation and basin discharge, so their uncertainties would have more impact.

4 Snow water equivalent (SWE)
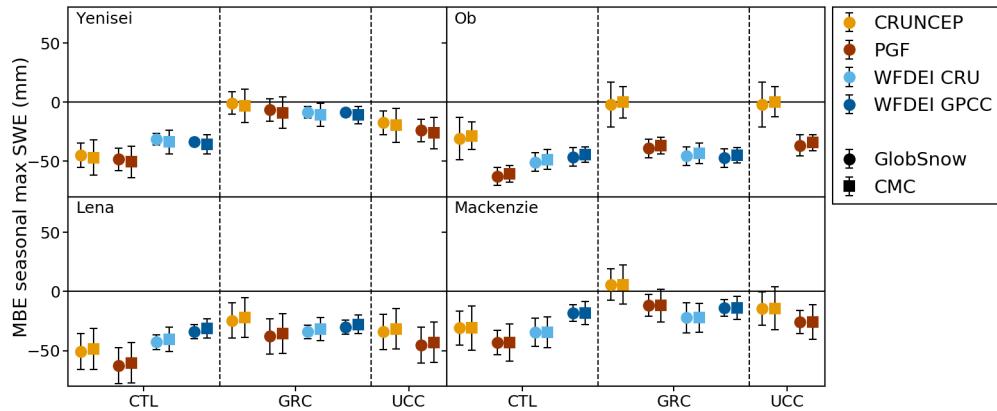
Figure S5: Mean bias error (MBE) of seasonal maximum SWE (mm), calculated for each basin over the common overlap period, 2002–2010. The error bars show the standard deviation, σ_b (Eq. 3). The improvement in the MBE in the GRC and UCC runs varies between basins (the Yenisei and Mackenzie are most improved) and between data sets (CRUNCEP is most improved in all basins).
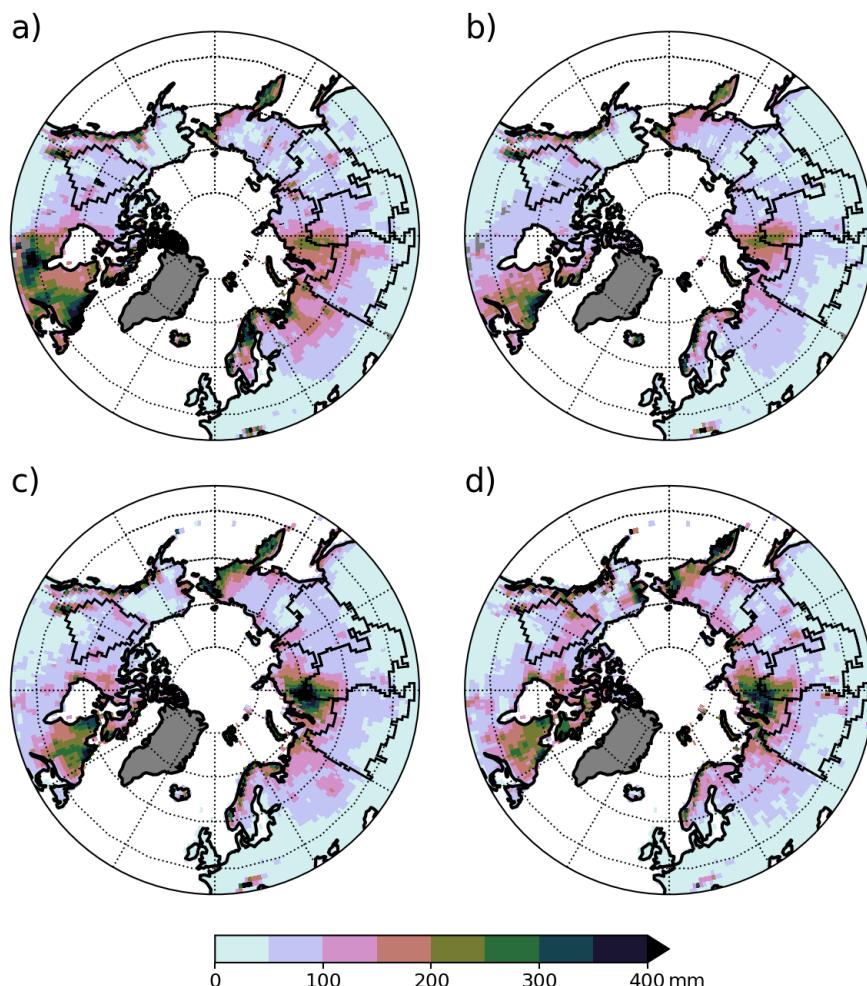
Figure S6: Modelled seasonal maximum SWE (mm), CTL runs for the common overlap period, 2002–2010. (a) CRUNCEP, (b) PGF, (c) WFDEI-CRU, (d) WFDEI-GPCC.
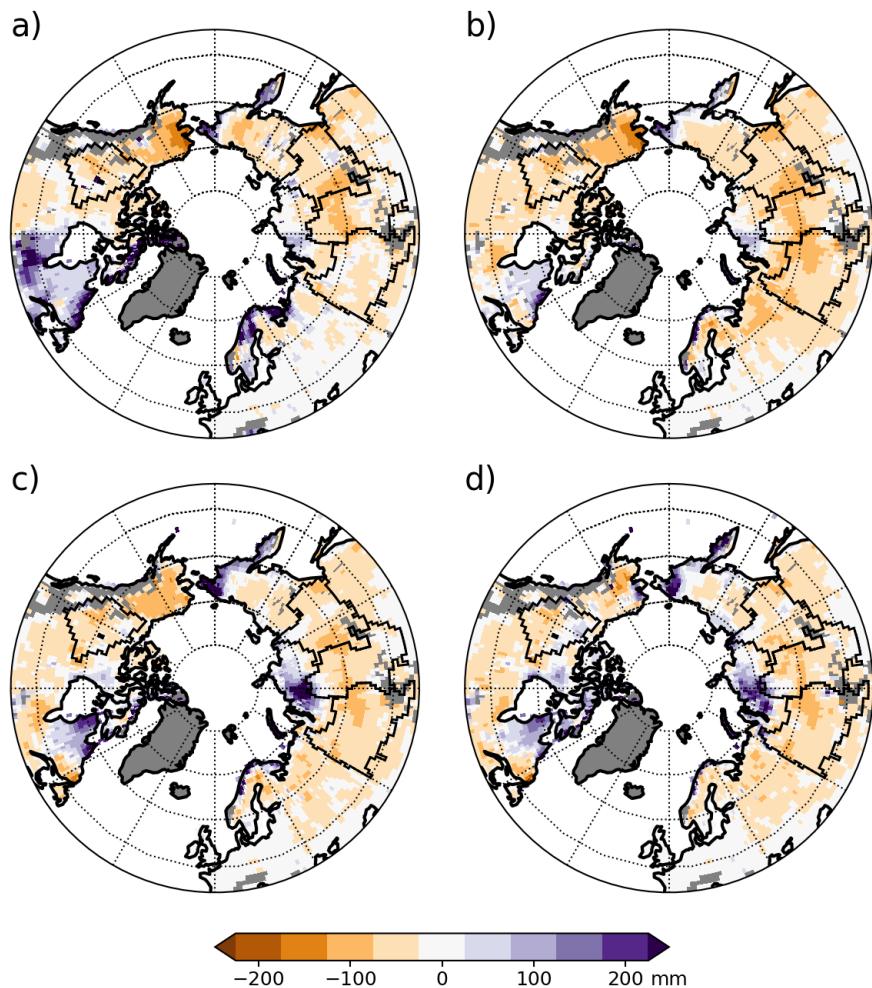
Figure S7: Difference modelled (CTL runs) and observed (GlobSnow) seasonal maximum SWE (mm) for the common overlap period, 2002–2010. (a) CRUNCEP, (b) PGF, (c) WFDEI-CRU, (d) WFDEI-GPCC. Although there are some regions where the SWE is overestimated, in general the seasonal maximum SWE in each basin is underestimated compared with both GlobSnow and CMC.
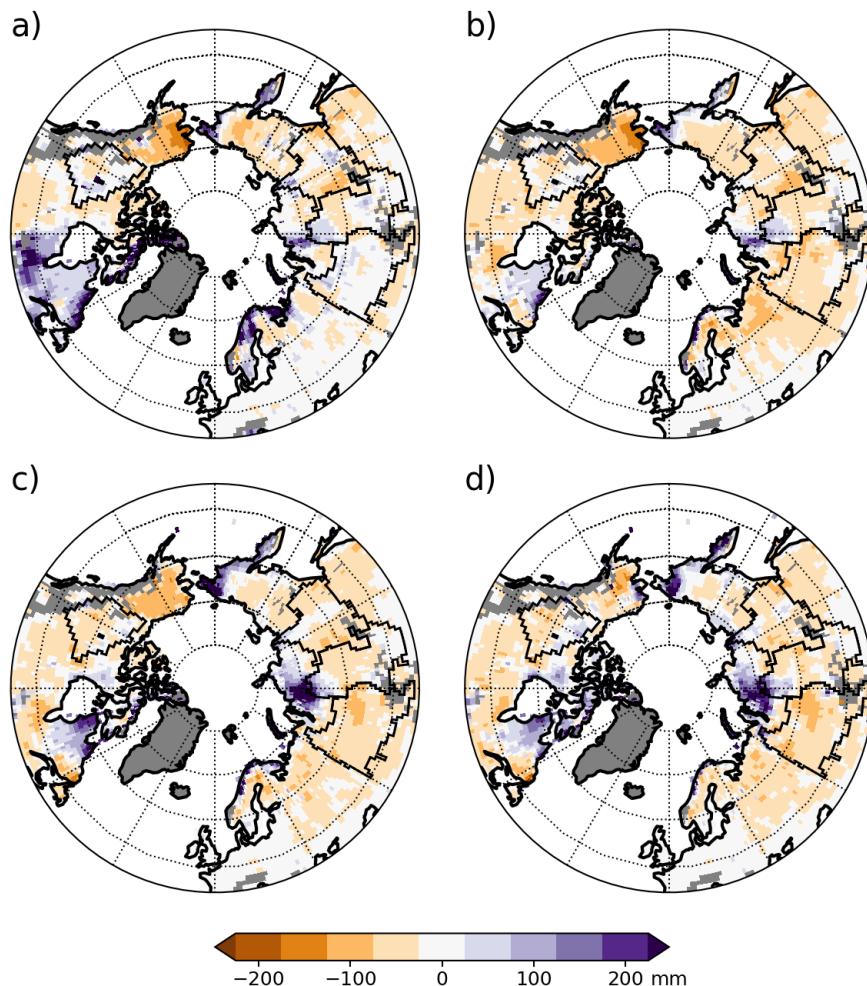
Figure S8: Difference between modelled (GRC runs) and observed (GlobSnow) seasonal maximum SWE (mm) for the common overlap period, 2002–2010. (a) CRUNCEP, (b) PGF, (c) WFDEI-CRU, (d) WFDEI-GPCC. Although there is still a general underestimation of SWE, the bias is reduced, and there are more regions of close agreement or overestimation.

5 Basin discharge
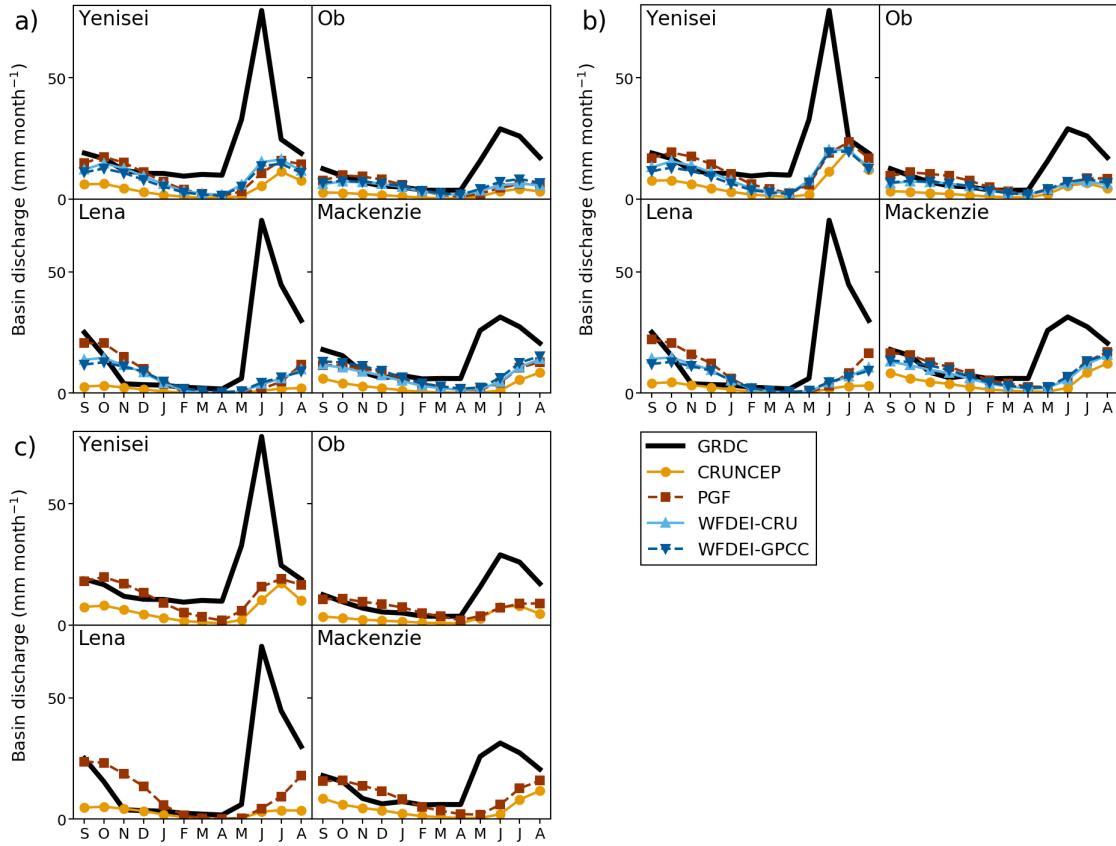
Figure S9: Mean-monthly climatology of basin discharge (mm month^{-1}) for (a) CTL runs, (b) GRC runs and (c) UCC runs, averaged over the common overlap period, 2002–2010. JULES fails to reproduce the timing and magnitude of the spring peak.

6 Water balance
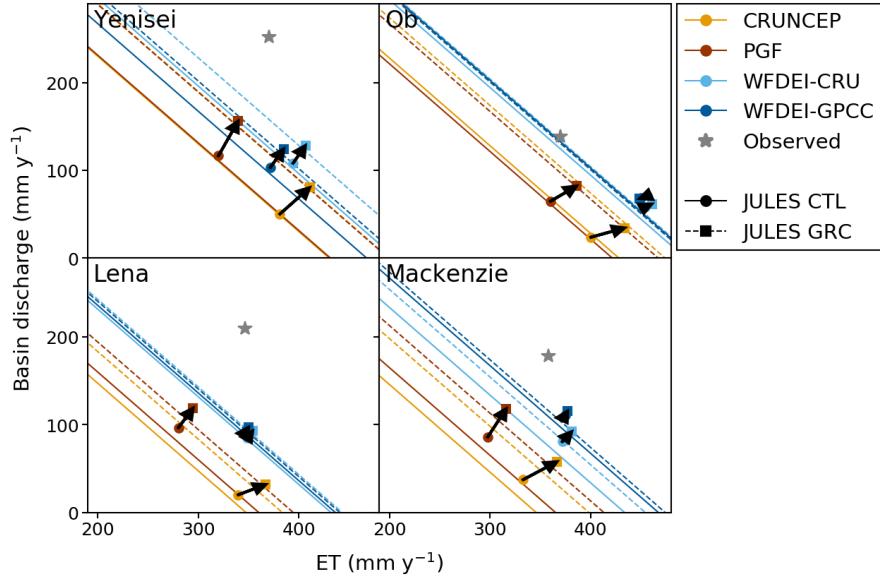
Figure S10: Annual basin discharge (mm y^{-1}) against annual evaporation flux (mm) for CTL and GRC runs 2002–2010. Lines show the precipitation limit (mm y^{-1}). Note that, although the x- and y-axis limits differ, the scales are the same, such that a unit change on one axis is the same length as a unit change on the other. The evaporation is several times larger than the basin discharge. The arrows show the direction of change between the CTL and GRC runs. A more vertical arrow shows that the increased cold season precipitation causes more increase in basin discharge (eg. PGF runs), while a more vertical arrow shows that the increase is more in the evaporation (eg. CRUNCEP runs).

7 Information about data sets and model runs

Table S1: GRDC data availability and use. The mean-monthly climatology was calculated over all the available data, then missing months and years gap-filled with this climatology.

Basin	Years available	Months missing	Years replaced with climatology
Yenisei	1936–2011		2012–2017
Ob	1930–2010	2000 (whole year)	2011–2017
Lena	1951–2002		2003–2017
Mackenzie	1972–2011	1972 (Jan, Feb, Apr, Jun)	2012–2017
		1997 (Nov, Dec)	
		1998 (Jan, Feb, Mar)	

Table S2: Rose suite IDs and revisions for each experiment. All are available from the repository at `https://code.metoffice.gov.uk/trac/roses-u` or through the browser at `https://code.metoffice.gov.uk/rosie/u` (registration required).

Experiment	Driving data	Rose id	Revision
CTL	CRUNCEP	u-at900	70155
	PGF	u-bb972	93780
	WFDEI-CRU	u-ao929	70151
	WFDEI-GPCC	u-av156	70158
GRC	CRUNCEP	u-aw333	85408
	PGF	u-bc394	94656
	WFDEI-CRU	u-aw349	85554
	WFDEI-GPCC	u-aw347	85494
UCC	CRUNCEP	u-av896	71361
	PGF	u-bc419	94745

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