Supplementary Materials for: "Increased mean annual temperatures in 2014-2019 indicate permafrost thaw in Alaskan National Parks"

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Table S1. Climate monitoring stations in the study area

Station Name	I&M Network[a]	Park Acronym[b]	Station ID	Latitude (degrees)	Longitude (degrees)	Elevation (m)	Start of Record
Devil Mtn.	ARCN	BELA	DVLA	66.296	-164.520	221	08/2011
Ella Creek	ARCN	BELA	ELLA	65.275	-163.820	709	09/2012
Hoodoo Hill	ARCN	BELA	HDOA	65.595	-163.411	472	06/1992
Serpentine	ARCN	BELA	SRTA	65.852	-164.708	143	08/2011
Mt. Noak	ARCN	CAKR	MNOA	67.141	-162.995	257	07/2011
Tahinichok	ARCN	CAKR	TAHA	67.550	-163.567	292	07/2011
Kavet Creek	ARCN	KOVA	KAVA	67.139	-159.044	72	06/1992
Salmon River	ARCN	KOVA	SRWA	67.460	-159.841	381	07/2011
Asik	ARCN	NOAT	ASIA	67.475	-162.266	410	07/2012
Howard Pass	ARCN	NOAT	HOWA	68.156	-156.896	642	07/2011
Imelyak	ARCN	NOAT	IMYA	67.545	-157.077	1099	07/2012
Kaluich	ARCN	NOAT	KAUA	67.573	-158.432	752	07/2012
Kelly Station	ARCN	NOAT	KELA	67.930	-162.280	94	07/2011
Noatak	ARCN	NOAT	KTZA	68.071	-158.704	300	04/1990
Kugururok	ARCN	NOAT	KUGA	68.317	-161.492	335	07/2014
Sisiak	ARCN	NOAT	SSIA	67.995	-160.396	567	07/2011
Chimney Lake	ARCN	GAAR	CHMA	67.714	-150.585	1166	08/2012
Killik Pass	ARCN	GAAR	KLIA	67.984	-155.013	1326	08/2012
Pamichtuk Lake	ARCN	GAAR	PAMA	67.766	-152.164	1019	08/2012
Ram Creek	ARCN	GAAR	RAMA	67.624	-154.345	1252	08/2012
Dunkle Hills	CAKN	DENA	DKLA	63.268	-149.542	819	08/2004
Eielson Visitor Center	CAKN	DENA	EVCA	63.431	-150.310	1141	07/2005
Ruth Glacier	CAKN	DENA	RUGA	62.709	-150.543	1026	09/2008
Stampede	CAKN	DENA	SMPA	63.752	-150.330	571	06/2003
Toklat	CAKN	DENA	TKLA	63.525	-150.046	925	07/2005
Wigand	CAKN	DENA	WIGA	63.814	-150.109	563	08/2008
Chicken Creek	CAKN	WRST	CREA	62.124	-141.847	1598	08/2004
Chititu	CAKN	WRST	CTUA	61.274	-142.621	1399	08/2004
Gates Glacier	CAKN	WRST	GGLA	61.606	-143.015	1330	07/2005
Tana Knob	CAKN	WRST	TANA	60.908	-142.901	1056	07/2005
Tebay	CAKN	WRST	TEBA	61.181	-144.339	584	07/2005
Coal Creek	CAKN	YUCH	CLCA	65.304	-143.157	278	09/2004
Upper Charley	CAKN	YUCH	UPRA	64.517	-143.202	1109	08/2005

[a]NPS Inventory and Monitoring Network: Arctic Network (ARCN) and Central Alaska Network (CAKN) (Fig. 1)

[b]Park acronyms and locations are given in Fig. 1

Table S2. Environmental conditions at the study monitoring stations[a]

Park Acronym	Station ID	Vegetation	Soil texture	Soil Coarse fragments (%)	Estimated active layer (m)	Median max snow depth (m)	Snowpack class
BELA	DVLA	Mesic graminoid herbaceous	Loam	10	0.9	0.29	tundra
BELA	ELLA	Lichen	Loamy coarse sand	90	2.4	0.45	tundra
BELA	HDOA	Open low scrub	Peat/clay	15	0.6	no data	tundra
BELA	SRTA	Open low scrub	Loam	20	no data	0.12	tundra-scoured
CAKR	MNOA	Dryas dwarf scrub	Sandy clay loam	35	3.8	0.43	tundra
CAKR	TAHA	Dryas dwarf scrub and Open low scrub	Sandy loam	80	2.5	0.16	tundra-scoured
KOVA	KAVA	Closed low scrub	Silt loam	0	talik	no data	taiga
KOVA	SRWA	Barren and Open low scrub	Sandy loam	75	3.6	0.97	alpine
NOAT	ASIA	Dryas dwarf scrub	Sandy loam	55	3.5	0.15	tundra-scoured
NOAT	HOWA	Barren and Dryas dwarf scrub	Sandy loam	75	2.4	no data	tundra-scoured
NOAT	IMYA	Barren and Dryas dwarf scrub	Sandy loam	85	1.7	no data	tundra-scoured
NOAT	KAUA	Dryas dwarf scrub	Sandy loam	65	1.9	0.38	tundra
NOAT	KELA	Open white spruce forest	no data	no data	no data	0.74	taiga
NOAT	KTZA	Open low scrub	Sandy clay loam	30	2.6	no data	tundra
NOAT	KUGA	Open low scrub	Loam	60	3.2	0.35	tundra
NOAT	SSIA	Dryas dwarf scrub and Ericaceous dwarf scrub	Sandy loam	45	2.0	0.05	tundra-scoured
GAAR	CHMA	Dryas dwarf scrub	Loam	75	1.6	0.11	tundra-scoured
GAAR	KLIA	Mesic graminoid herbaceous	Sandy clay loam	60	1.2	0.13	tundra-scoured
GAAR	PAMA	Dryas dwarf scrub	Sandy clay loam	35	1.3	0.13	tundra-scoured
GAAR	RAMA	Dryas dwarf scrub	Sandy loam	50	3.4	0.31	tundra
DENA	DKLA	Open low scrub	Sandy loam	30	no pf	0.71	alpine
DENA	EVCA	Closed low scrub	no data	no data	no data	0.25	tundra
DENA	RUGA	Lichen and Willow dwarf scrub	no data	no data	no data	1.09	alpine
DENA	SMPA	Lichen	Coarse sand	75	no pf	0.54	taiga
DENA	TKLA	Open tall scrub	no data	Estimated >50	no pf	0.27	tundra
DENA	WIGA	Open low scrub	Peat/silt loam	0	0.8	0.27	tundra
WRST	CREA	Dryas dwarf scrub	Sandy loam	65	1.7	0.24	tundra

Park Acronym	Station ID	Vegetation	Soil texture	Soil Coarse fragments (%)	Estimated active layer (m)	Median max snow depth (m)	Snowpack class
WRST	CTUA	Dryas dwarf scrub	Loam	0	1.5	no data	tundra-scoured
WRST	GGLA	Mesic forb herbaceous	Loam	70	no pf	1.59	alpine
WRST	TANA	Open low scrub	Loamy sand	50	no pf	1.72	alpine
WRST	TEBA	Mesic forb herbaceous	Loamy sand	75	no pf	1.44	alpine
YUCH	CLCA	Bryophyte	Peat	0	0.6	0.55	taiga
YUCH	UPRA	Open low scrub	Loamy coarse sand	30	3.3	0.47	taiga

[a]Column definitions:
Park Acronym: see Fig. 1.
Station ID: see Table S1
Vegetation: Alaska vegetation classification level III (Viereck et al. 1992)
Soil texture: dominant USDA soil textural class (Soil Survey Division Staff 1993) in the fine earth (< 2 mm) fraction of the top 50 cm.
Soil Coarse fragments, %: estimated average fraction of coarse fragments (> 2 mm) by volume in the 0 to 50 cm layer.
Estimated active layer, m: estimated by extrapolation from a linear regression of (thaw degree-days)$^{0.5}$ vs. sensor depth for ground temperature sensors. In a homogenous material, thaw depth below the surface or any below depth in the active layer is approximately proportional to the square root of thaw-degree days at that depth (Riseborough 2003). "No data" stations lack ground sensors or (station SRTA) had non-significant linear regressions. "No pf" means permafrost was not present, "talik" means permafrost is likely to be present but beneath a deep talik (thawed zone).
Median max snow depth, m: median of maximum daily snow depth reading by ultrasonic sensor.
Snowpack class: by the classification system of Sturm et al. (1995); stations with a "tundra" snowpack that was very thin due to high winds (median maximum snow depth less than 0.2 m) are labeled "tundra-scoured"

Table S2 References

Riseborough, D. W. 2003. Thawing and freezing indices in the active layer. Proceedings of the 8th International Conference on Permafrost, vol. 2, 953–58. Zurich, Switzerland: Rotterdam: AA Balkema. https://www.arlis.org/docs/vol1/ICOP/55700698/Pdf/Chapter_167.pdf.

Soil Survey Division Staff. 1993. Soil survey manual. U.S. Department of Agriculture Handbook 18. Washington, DC: Soil Conservation Service.

Sturm, M., J. Holmgren, and G. E. Liston. 1995. A seasonal snow cover classification system for local to global applications. Journal of Climate 8 (5):1261–83.

Viereck, L. A., C. T. Dyrness, A. R. Batten, and K. J. Wenzlick. 1992. The Alaska vegetation classification. General Technical Report PNW-GTR-286. Portland, Oregon: USDA Forest Service, Pacific Northwest Research Station. http://www.fs.fed.us/pnw/publications/pnw_gtr286/.

Table S3. Average ground temperature thermal offset relative to 10 cm depth

	Thermal offset (°C) at indicated depth and (years of data)			
Park_Station	**20 cm**	**50 cm**	**75 cm**	**100 cm**
BELA_DVLA	0.1 (6)	-0.4 (7)		
BELA_ELLA	0.2 (5)	-0.2 (5)		
BELA_HDOA	-0.2 (1)	-0.2 (1)		
BELA_MITI	0.2 (5)	-0.2 (5)		
BELA_SRTA	-0.1 (5)	0.4 (5)		
CAKR_MNOA	0.1 (7)	-0.6 (5)	-0.6 (5)	
CAKR_TAHA	-0.1 (4)	-0.3 (4)	-0.2 (4)	
GAAR_CHMA	-0.1 (5)	0.4 (5)	0.4 (5)	
GAAR_KLIA	0.2 (6)	-0.1 (6)		
GAAR_PAMA	-0.1 (4)	-0.3 (4)		
GAAR_RAMA	0.1 (4)	0.1 (4)		
KOVA_KAVA	-0.2 (4)	-0.2 (3)		
KOVA_SRWA	0.0 (5)	0.2 (5)		
NOAT_ASIA	-0.1 (5)	-0.2 (6)		
NOAT_HOWA	-0.1 (5)	0.1 (3)		
NOAT_IMYA	-0.5 (6)	-0.4 (6)		
NOAT_KAUA	0.0 (6)	0.1 (6)		
NOAT_KTZA	0.0 (1)	-0.2 (1)		
NOAT_KUGA	0.3 (5)	0.4 (5)		
DENA_DKLA	0.0 (10)	-0.2 (2)		
DENA_RUGA	0.2 (3)	0.7 (3)		
DENA_SMPA	0.0 (0)	0.0 (11)		
DENA_TKLA	-0.4 (3)	-0.5 (3)		
DENA_WIGA	-0.6 (6)	-1.0 (6)		
NOAT_SSIA	-0.3 (6)	-0.2 (4)	-0.3 (2)	
WRST_CREA	-0.5 (9)	-0.5 (9)		-0.5 (5)
WRST_CTUA	-0.5 (8)	-0.2 (9)		
WRST_GGLA	0.1 (6)	0.1 (6)		
WRST_TANA	0.1 (7)	-0.4 (2)		
WRST_TEBA	0.0 (6)	-0.3 (6)		
YUCH_CLCA	0.0 (0)	-0.4 (13)		-0.4 (13)
YUCH_UPRA	0.1 (6)	0.2 (6)		

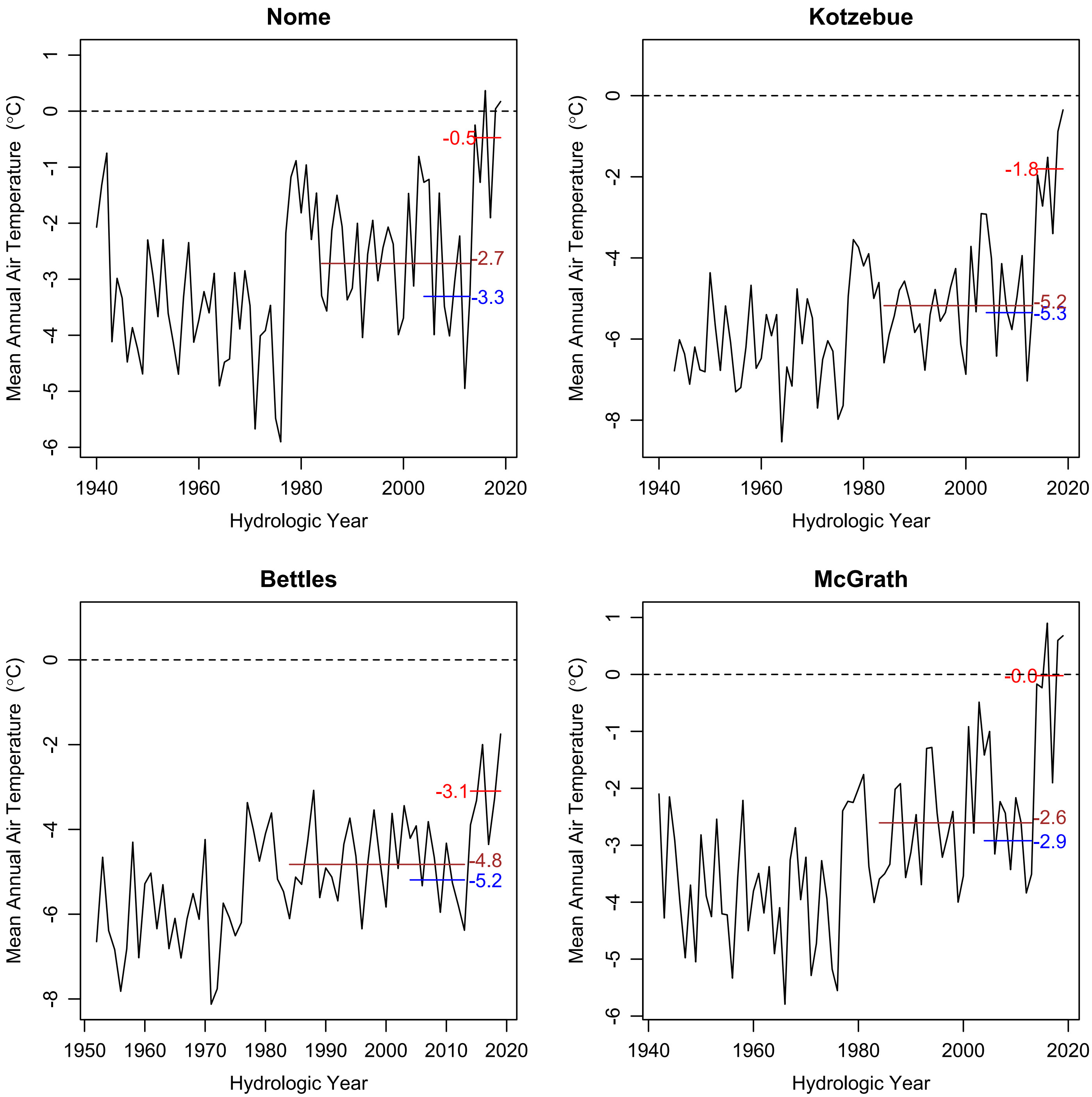

Figure S1. Mean annual air temperatures at Nome, Kotzebue, Bettles, and McGrath, Alaska. Multi-year means are shown for 1984-2013 (brown), 2006-2013 (blue), and 2014-2019 (red).

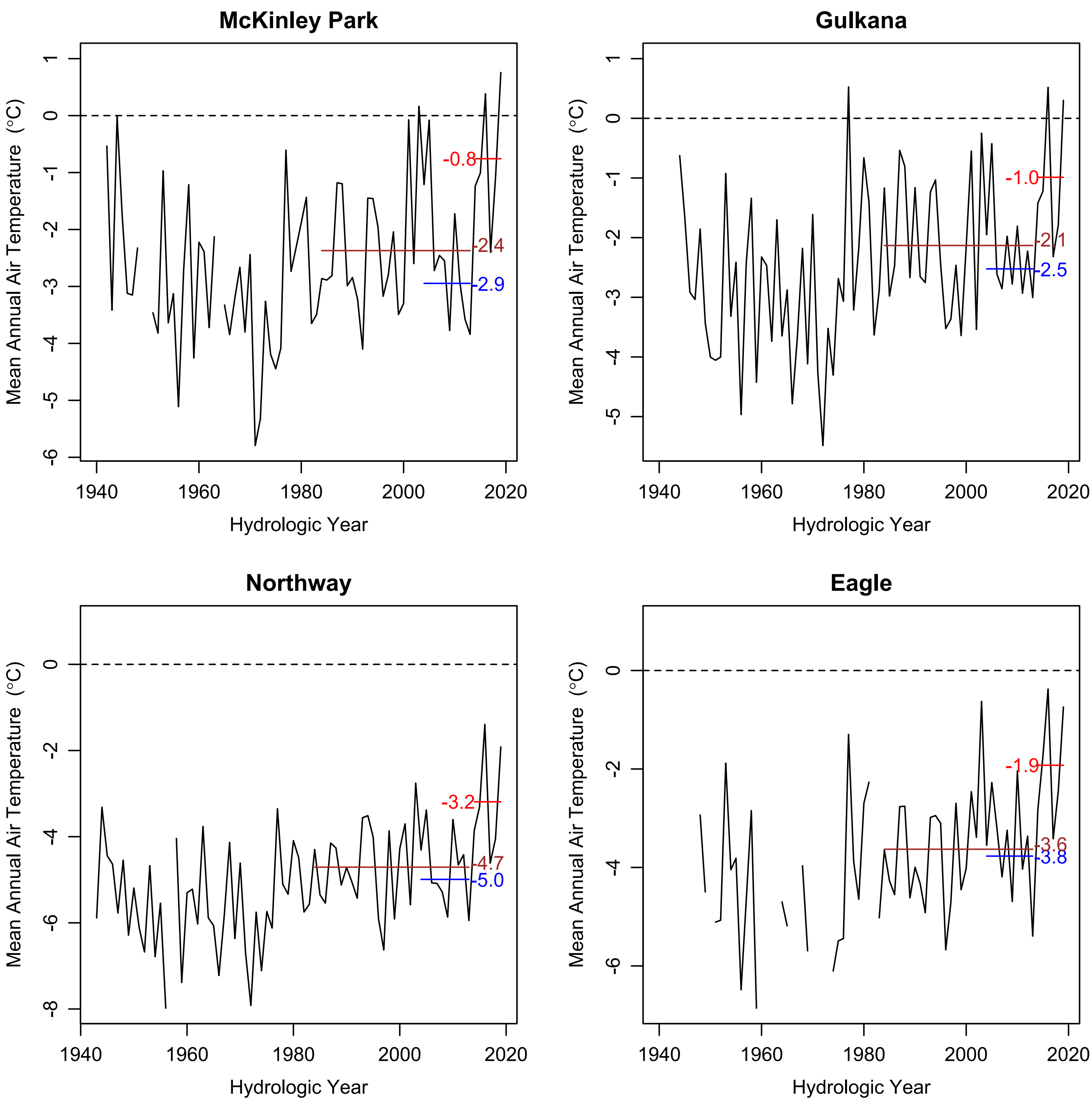

Figure S2. Mean annual air temperatures at McKinley Park, Gulkana, Northway, and Eagle, Alaska. Multi-year means are shown for 1984-2013 (brown), 2006-2013 (blue), and 2014-2019 (red).

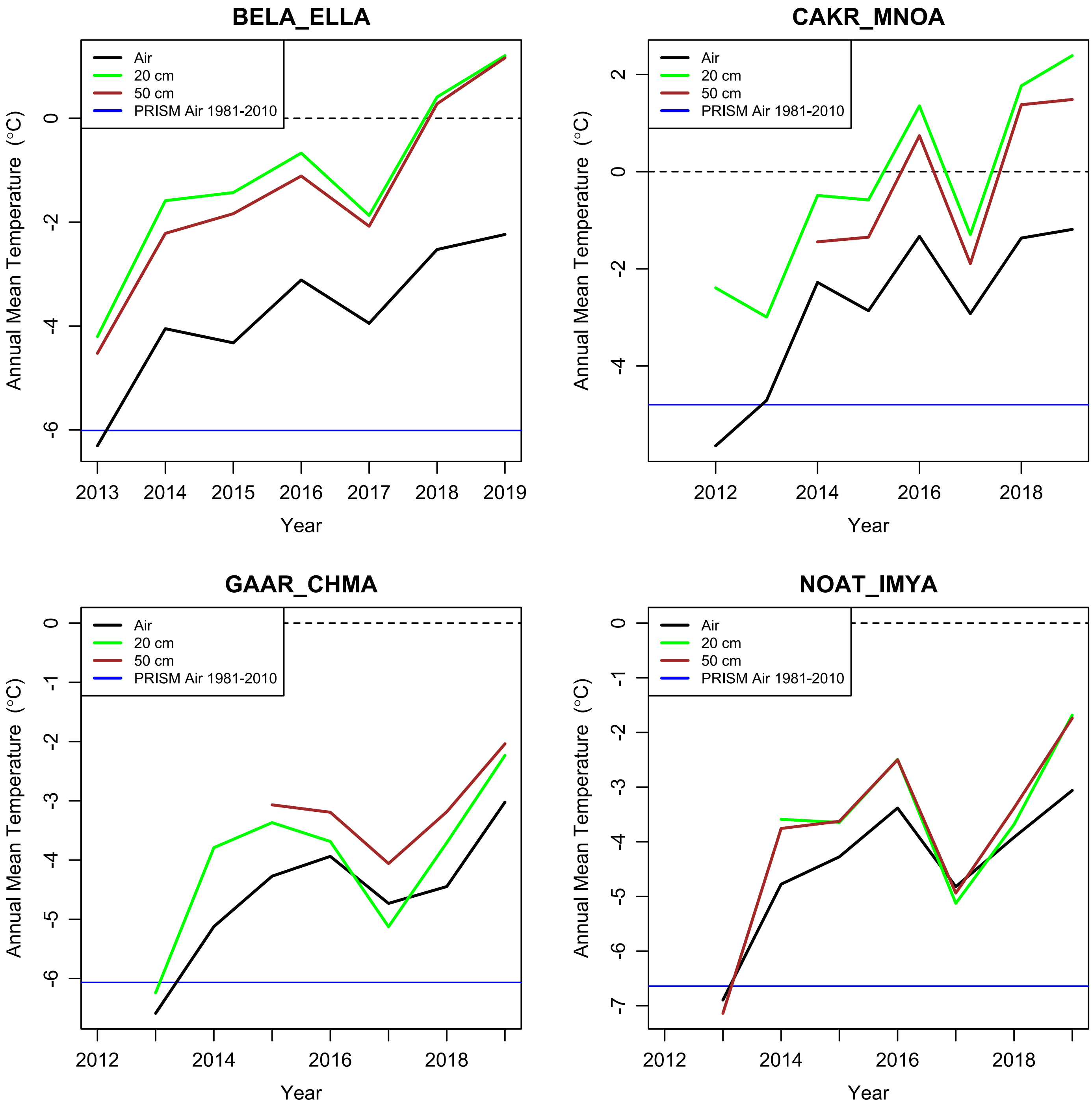

Figure S3. Mean annual air and ground temperatures at example stations in the Arctic Alaskan parks. BELA_ELLA is in alpine tundra and had 1981-2010 modeled MAAT (PRISM Climate Group, 2020) and observed 2013 MAAT of about -6°C. MAGT rose from -4.5°C in 2013 to slightly above 0°C in 2018-2019, suggesting destabilization of permafrost. CAKR_MNOA represents lowland tundra in the northwestern part of our study area. Mean annual air temperatures in 2014-2019 increased by more than 2°C relative to 2012-2013 and the modeled 1981-2010 values means. Mean annual ground temperatures after 2014 fluctuated near 0°C, indicating marginal permafrost stability. GAAR_CHMA and NOAT_IMYA are in alpine tundra in north-western Alaska, further inland than the preceding stations. The thin snow cover causes the MAGTs to be only slightly higher than MAATs. The 2013 MAAT and PRISM modeled values suggest MAATs of -6°C to -7°C prior to 2014. Post-2014 MAATs have been 1-3°C higher than the presumed long-term average, and the MAGTs in 2019 rose to about -2°C.

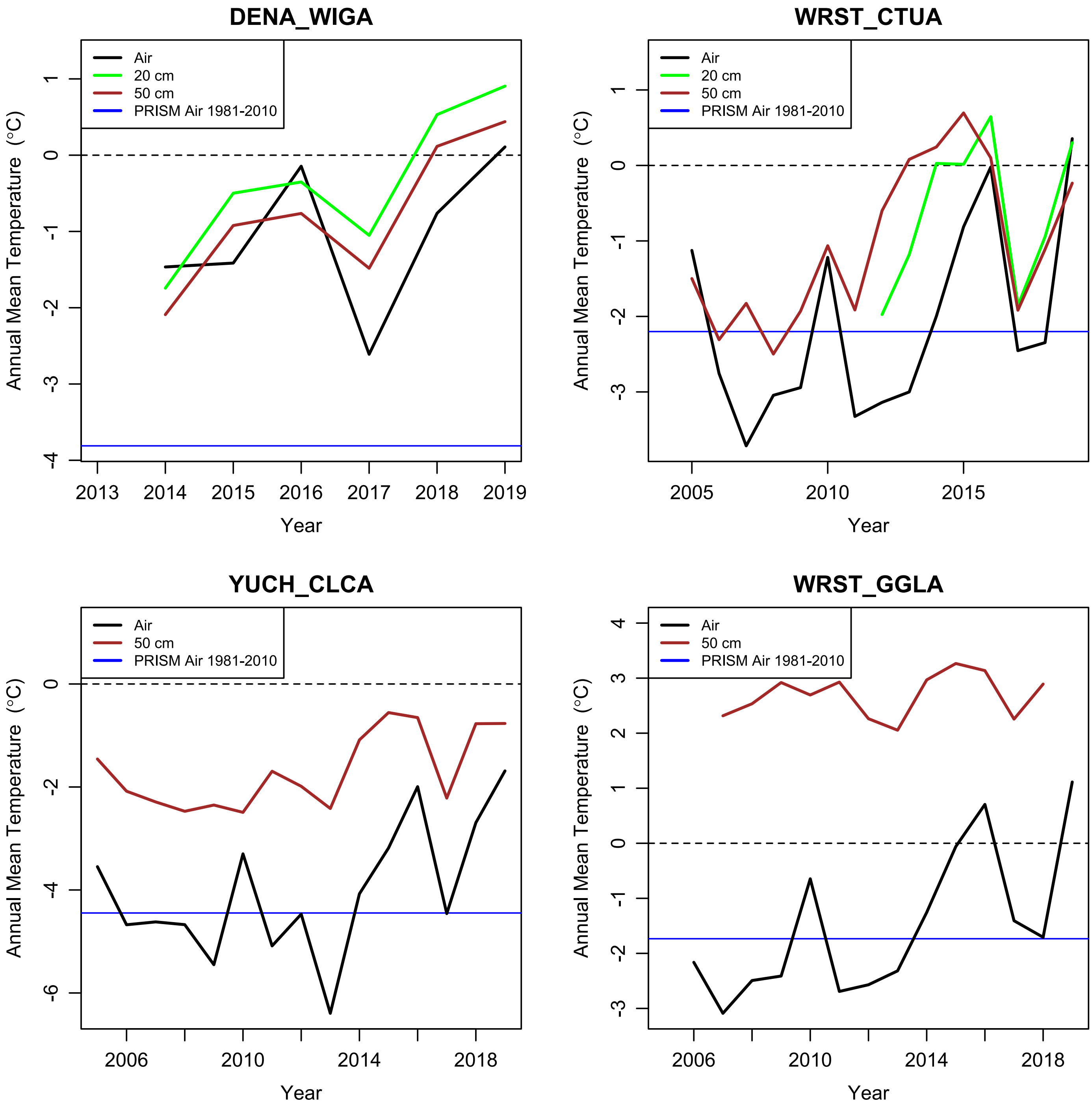

Figure S4. Mean annual air and ground temperatures at example stations in the central Alaskan parks. Station DENA_WIGA is in central Alaska on windswept lowlands with poorly drained permafrost soils. It lacks pre-2014 data, but data from the nearby station DENA_SMPA confirms the pre-2014 modeled MAAT by PRISM Climate Group (2020) of about -4°C. Post-2014 MAATs have been 0 to -3°C and MAGTs rose to slightly above 0°C in 2018-19, indicating incipient destabilization of permafrost. WRST_CTUA, on an alpine ridge in east-central Alaska, had pre-2014 air and ground temperatures near -2°C. In recent years both the mean annual ground and air temperatures fluctuated between about -2°C and slightly above 0°C. YUCH_CLCA is a typical lowland interior taiga location with permafrost and a 2006-2014 MAAT average of -4.8°C. MAATs as high as -2°C in several recent years caused MAGTs to rise as high as -0.6°C, but they still remained below freezing. WRST_GGLA is on an alpine ridge with deep snow cover and no permafrost; it had MAGTs well above freezing even prior to the 2014 warming. MAGTs displayed little change after 2014, even as MAATs rose above freezing in some years.