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

David K Swanson*, Pamela J. Sousanes, and Ken Hill. December, 2020.

*Corresponding author, david_k_swanson@nps.gov, IRCID ID: 0000-0002-8732-5355

Table S1. Climate monitoring stations in the study area

| Station Name      | I&M Networka | Park Acronymb | 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         |
| Tahninchok         | ARCN         | CAKR          | TAHU       | 67.550             | -163.567            | 292          | 07/2011         |
| Kavet Creek        | ARCN         | KOVA          | KAVA       | 67.139             | -165.044            | 70           | 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          | KAUU       | 67.573             | -158.432            | 752          | 07/2012         |
| Kelly Station      | ARCN         | NOAT          | KELA       | 67.930             | -158.280            | 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          | KLLA       | 67.984             | -155.013            | 1326         | 08/2012         |
| Pamichuk 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         | DEMA          | DKLA       | 63.268             | -149.542            | 819          | 08/2004         |
| Eielson Visitor    | CAKN         | DEMA          | EVCA       | 63.431             | -150.310            | 1141         | 07/2005         |
| Center             |              |               |            |                    |                     |              |                 |
| Ruth Glacier       | CAKN         | DEMA          | RUGA       | 62.709             | -150.543            | 1026         | 09/2008         |
| Stampede           | CAKN         | DEMA          | SMPA       | 63.752             | -150.330            | 571          | 06/2003         |
| Toklat             | CAKN         | DEMA          | TKLA       | 63.525             | -150.046            | 925          | 07/2005         |
| Wigand             | CAKN         | DEMA          | WIGA       | 63.814             | -150.109            | 563          | 08/2008         |
| Chicken Creek      | CAKN         | WRST          | CREA       | 62.124             | -141.847            | 1598         | 08/2004         |
| Chittitu           | 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       | 61.811             | -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         |

aNPS Inventory and Monitoring Network: Arctic Network (ARCN) and Central Alaska Network (CAKN) (Fig. 1)

bPark acronyms and locations are given in Fig. 1
Table S2. Environmental conditions at the study monitoring stations

| 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 Lichen | Loam | 10 | 0.9 | 0.29 | tundra |
| BELA         | ELLA       | Mesic graminoid herbaceous Lichen | Loamy coarse sand Peat/clay Loam | 90 | 2.4 | 0.45 | tundra |
| BELA         | HDOA       | Open low scrub | Loam | 15 | 0.6 | no data | tundra |
| BELA         | SRTA       | Open low scrub | Loam | 20 | no data | 0.12 | tundra |
| CAKR         | MNOA       | Dryas dwarf scrub | Sandy clay loam | 35 | 3.8 | 0.43 | tundra |
| CAKR         | TAHA       | Dryas dwarf scrub | Sandy loam | 80 | 2.5 | 0.16 | tundra |
| KOVA         | KAVA       | Closed low scrub | Silt loam Sandy 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 |
| NOAT         | HOWA       | Barren and Dryas dwarf scrub | Sandy loam | 75 | 2.4 | no data | tundra |
| NOAT         | IMYA       | Barren and Dryas dwarf scrub | Sandy loam | 85 | 1.7 | no data | tundra |
| 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 loam | 30 | 2.6 | no data | tundra |
| NOAT         | KUGA       | Open low scrub | Loam | 60 | 3.2 | 0.35 | tundra |
| NOAT         | SSIA       | Dryas dwarf scrub | Sandy loam | 45 | 2.0 | 0.05 | tundra |
| GAAR         | CHMA       | Dryas dwarf scrub | Loam | 75 | 1.6 | 0.11 | tundra |
| GAAR         | KLIA       | Mesic graminoid herbaceous Lichen | Sandy loam | 60 | 1.2 | 0.13 | tundra |
| GAAR         | PAMA       | Dryas dwarf scrub | Sandy clay loam | 35 | 1.3 | 0.13 | tundra |
| 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 | Sandy loam | no data | no data | no data | tundra |
| DENA         | RUGA       | Lichen and Willow dwarf scrub | Peat/silt loam | no data | no data | no data | tundra |
| DENA         | SMPA       | Coarse sand | no data | 75 | no pf | 0.54 | taiga |
| DENA         | TKLA       | Open tall scrub | Estimated >50 | no pf | 0.27 | tundra |
| DENA         | WIGA       | Open low scrub | Sandy loam | 65 | 1.7 | 0.24 | tundra |
| WRST         | CREA       | Dryas dwarf scrub | | | | | |
| 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 alpine |
| 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           |

*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

| Park_Station | 20 cm | 50 cm | 75 cm | 100 cm |
|--------------|-------|-------|-------|--------|
| BELA_DVLA    | 0.1   | -0.4  |       |        |
| BELA_ELLA    | 0.2   | -0.2  |       |        |
| BELA_HDOA    | -0.2  | -0.2  |       |        |
| BELA_MITI    | 0.2   | -0.2  |       |        |
| BELA_SRTA    | -0.1  | 0.4   |       |        |
| CAKR_MNOA    | 0.1   | -0.6  | -0.6  |        |
| CAKR_TAHA    | -0.1  | -0.3  | -0.2  |        |
| GAAR_CHMA    | -0.1  | 0.4   | 0.4   |        |
| GAAR_KLIA    | 0.2   | -0.1  |       |        |
| GAAR_PAMA    | -0.1  | -0.3  |       |        |
| GAAR_RAMAG   | 0.1   | 0.1   |       |        |
| KOVA_KAVA    | -0.2  | -0.2  |       |        |
| KOVA_SRWA    | 0.0   | 0.2   |       |        |
| NOAT_Asia    | -0.1  | -0.2  |       |        |
| NOAT_HOWA    | -0.1  | 0.1   |       |        |
| NOAT_IMYA    | -0.5  | -0.4  |       |        |
| NOAT_KAUA    | 0.0   | 0.1   |       |        |
| NOAT_KTZA    | 0.0   | -0.2  |       |        |
| NOAT_KUGA    | 0.3   | 0.4   |       |        |
| DENA_DKLA    | 0.0   | -0.2  |       |        |
| DENA_RUGA    | 0.2   | 0.7   |       |        |
| DENA_SMPA    | 0.0   | 0.0   |       |        |
| DENA_TKLA    | -0.4  | -0.5  |       |        |
| DENA_WIGA    | -0.6  | -1.0  |       |        |
| NOAT_SSIA    | -0.3  | -0.2  | -0.3  |        |
| WRST_CREA    | -0.5  | -0.5  | -0.5  |        |
| WRST_CTUA    | -0.5  | -0.2  |       |        |
| WRST_GGLA    | 0.1   | 0.1   |       |        |
| WRST_TANA    | 0.1   | -0.4  |       |        |
| WRST_TEBA    | 0.0   | -0.3  |       |        |
| YUCH_CLCA    | 0.0   | -0.4  | -0.4  |        |
| YUCH_UPRA    | 0.1   | 0.2   |       |        |
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.