Introduction

This supporting information provides Supplementary Figures and Tables, organized as follows:

1. Figure S1 provides a map delineating the spatial divisions of four Arctic sub-regions utilized for computing area-averaged results of AR occurrence frequency, surface energy budget (SEB) terms, surface temperature and T-2m, as presented in Table 1 and Table S1-S3.

2. Figure S2-S3 illustrates the spatial distributions of 40-year mean climatology, mean composite anomalies during the presence of AR events, and the relative contributions of the total anomalies to the mean SEB during each season, for sensible heat flux (SH) and latent heat flux (LH), respectively.

3. Figure S4 visualizes the 85th percentile climatological threshold of integrated water vapor transport (IVT) in ERA5 for January, spanning from 1980 to 2019. This figure serves as a representative of winter and facilitates the analysis of differences between the 85th_IVT AR index and M23 AR index results.

4. Table S1 displays regional average results of the 40-year average climatology, composite anomalies during AR events, the corresponding total contribution to the net SEB, and the extra AR contribution relative to the AR frequency for net surface longwave radiation (LWN), net surface shortwave radiation (SWN), and turbulent heat flux (TH).

5. Table S2 presents the regional average results for the 40-year mean climatology and composite anomalies during AR events for surface temperature and T-2m air temperature.

6. Table S3, based on the M23 AR index, provides the regional results for AR occurrence frequency, downward longwave radiation (LWD) anomalies during AR events, the relative contribution of total AR LWD anomalies to the mean SEB, along with the extra AR contribution relative to the corresponding AR frequency.

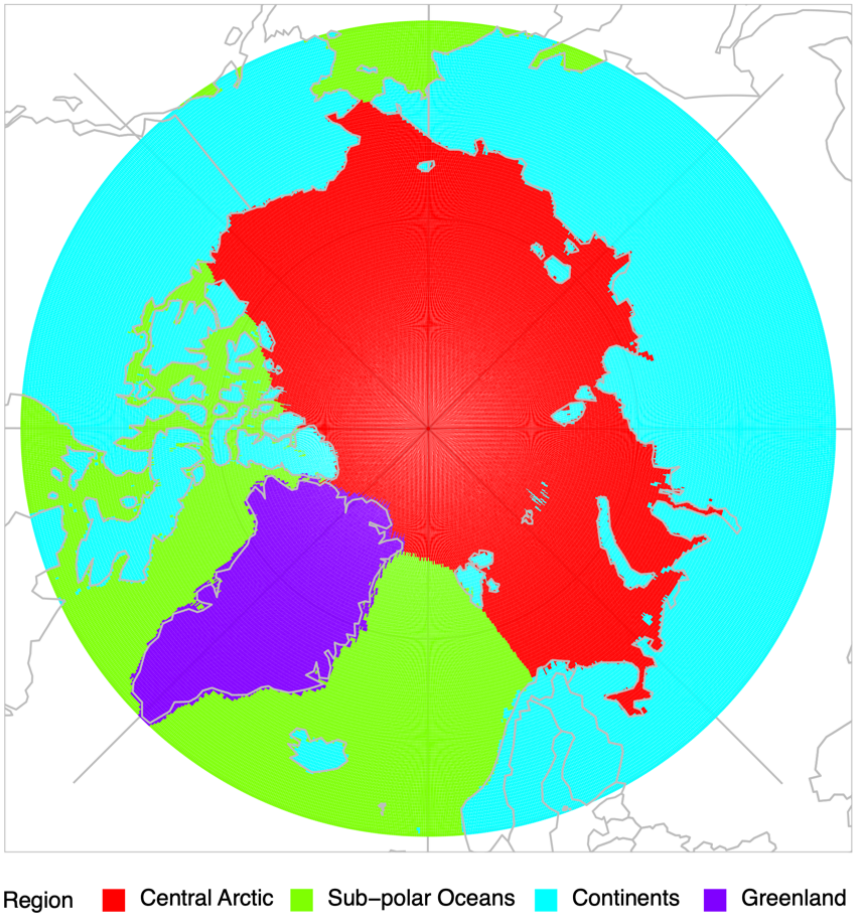

Figure S1. Map showing the spatial division of four sub-regions for calculating area averages of AR occurrence frequency, surface energy budget terms, T-2m and surface temperature, as presented in Table 1 and Table S1-S3. The central Arctic, including the Barents and Kara Seas, is highlighted in red; Sub-polar oceans in green; Continents in cyan; and Greenland in purple.

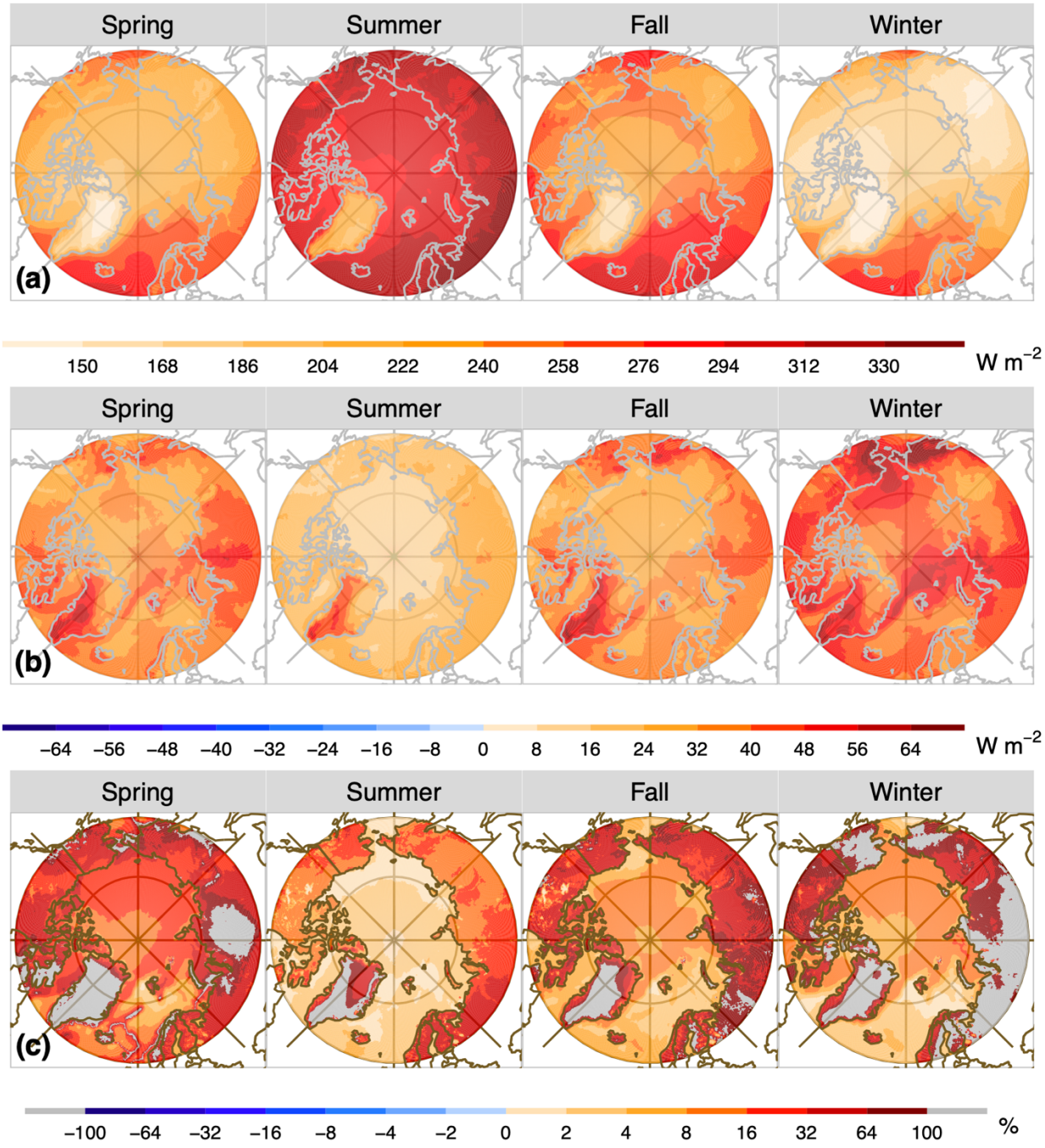

Figure S2. Maps showing (a) the spatial distributions of 40-year mean sensible heat flux (SH, unit: W m^{-2}) across Spring (March-May), Summer (June-August), Fall (September-November), and Winter (December-February) from 1980 to 2019. (b) spatial distributions of 40-year mean SH anomalies (unit: W m^{-2}) during the presence of AR events within each season. (c) Spatial distributions of the fraction of 40-year AR contribution (unit: %) from the total SH anomalies to the absolute values of 40-year mean SEB for each season. Note that all positive vertical fluxes values directed downwards towards the surface.

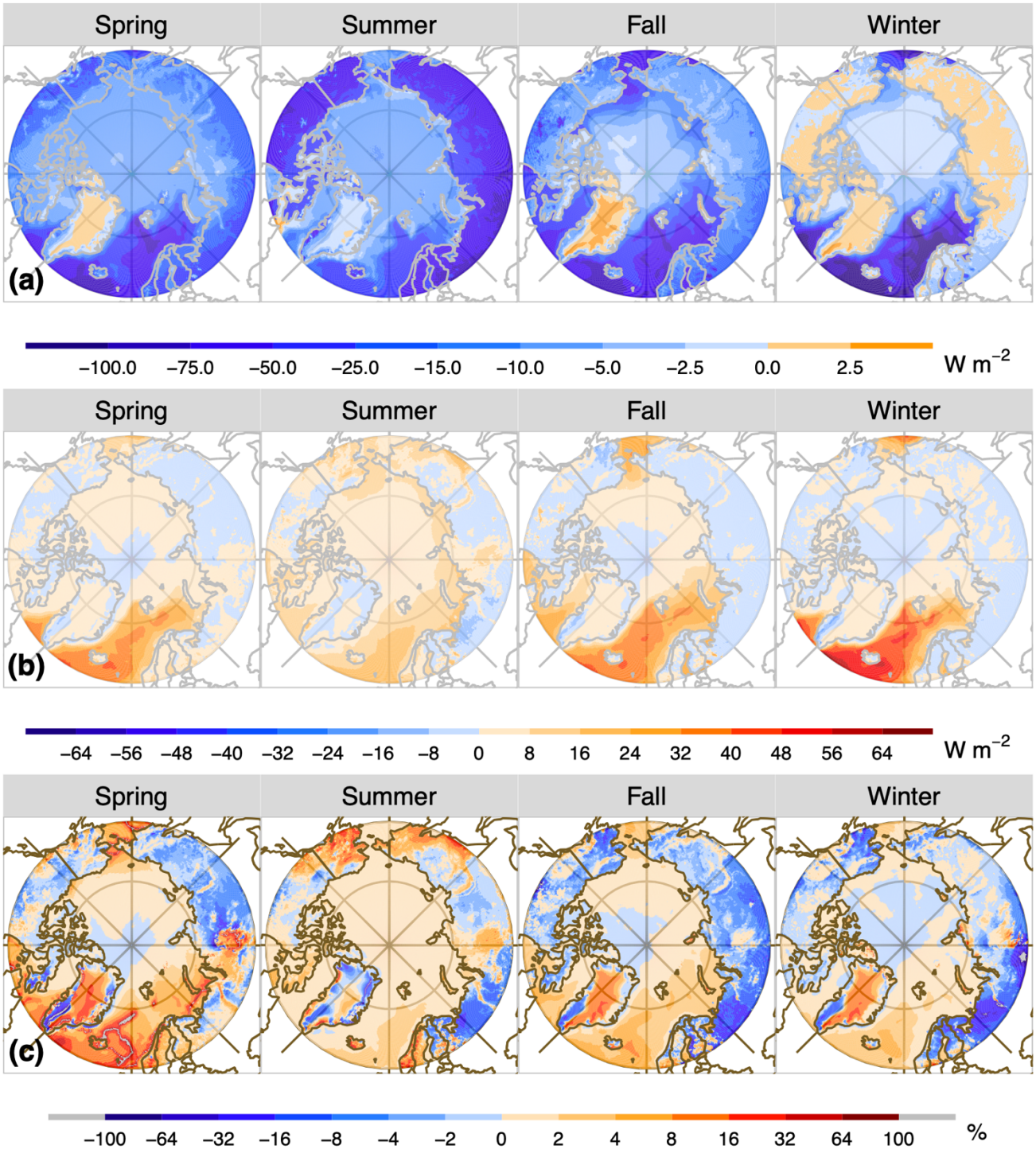

Figure S3. Similar to Figure S2, but for results according to the surface latent heat flux (LH).

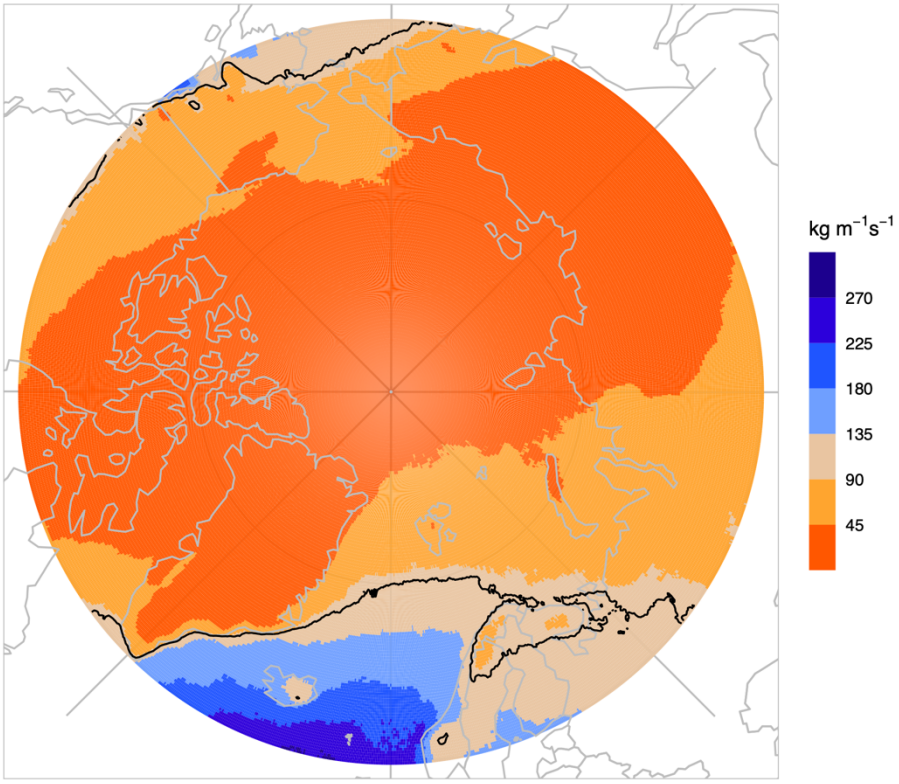

Figure S4. The 85th percentile climatological threshold of IVT in ERA5 (unit: kg m^{-1} s^{-1}) for January from 1980 to 2019, the black line is the 100 kg m^{-1} s^{-1} minimum criteria values that the M23 AR detection algorithm applies to complement the 85th percentile climate threshold.

Surface Net Longwave Radiation (LWN)								
Region	Central Arctic	Subpolar Oceans	Continents	Greenland	Central Arctic	Subpolar Oceans	Continents	Greenland
Season	Spring				Summer			
AR Freq. (%)	10.8	12.3	12.2	12.2	10.4	11.8	11.6	11.1
Climatology (W m^{-2})	-39.5	-50.3	-47.3	-47.5	-23.2	-34.4	-53.4	-51.3
Anomalies (W m^{-2})	17.1	27.4	16.6	20.4	13.8	21.1	17	22.1
Cotrib. to SEB (%)	20.8	49.3	95.1	2618.8	2.2	2.6	13.2	101.9
Extra AR (%)	10	37	82.9	2606.6	-8.2	-9.2	1.6	90.8
Season	Fall				Winter			
AR Freq. (%)	10.6	12.4	12.5	11.8	10.5	12.3	12.7	12.4
Climatology (W m^{-2})	-33.6	-50.7	-34.9	-39.2	-43.8	-56.3	-27.1	-37.7
Anomalies (W m^{-2})	16.2	29.9	13.9	20.8	21.8	31.2	11.5	18.1
Cotrib. to SEB (%)	4.2	4.6	19.6	41.8	4.4	3.3	41.3	52
Extra AR (%)	-6.4	-7.8	7.1	30	-6.1	-9	28.6	39.6

Surface Net Shortwave Radiation (SWN)								
Region	Central Arctic	Subpolar Oceans	Continents	Greenland	Central Arctic	Subpolar Oceans	Continents	Greenland
Season	Spring				Summer			
AR Freq. (%)	10.8	12.3	12.2	12.2	10.4	11.8	11.6	11.1
Climatology (W m^{-2})	36.4	86.1	81.8	34.8	99.9	153.8	156.6	64.9
Anomalies (W m^{-2})	-6.2	-29.4	-16.5	-7.5	-22	-52	-34.5	-17.4
Cotrib. to SEB (%)	-7.7	-50.7	-66.6	-553.6	-3.5	-6.2	-27.3	-46.6
Extra AR (%)	-3.1	38.4	54.4	541.4	-6.9	-5.6	15.7	35.5
Season	Fall				Winter			
AR Freq. (%)	10.6	12.4	12.5	11.8	10.5	12.3	12.7	12.4
Climatology (W m^{-2})	10.9	33	31	9.7	0.4	5.6	5.8	1.1
Anomalies (W m^{-2})	-2.6	-14.4	-8.3	-3.3	-0.1	-2.3	-1.5	-0.4
Cotrib. to SEB (%)	-0.6	-2.2	-12.3	-4.7	0	-0.2	-7.8	-0.5
Extra AR (%)	-10	-10.2	-0.2	-7.1	-10.5	-12.1	-4.9	-11.9

Turbulent Heat Flux (TH)								
Region	Central Arctic	Subpolar Oceans	Continents	Greenland	Central Arctic	Subpolar Oceans	Continents	Greenland
Season	Spring				Summer			
AR Freq. (%)	10.8	12.3	12.2	12.2	10.4	11.8	11.6	11.1
Climatology (W m^{-2})	-16.5	-57.5	-25.2	13.1	-7	-15.5	-81.3	-0.9
Anomalies (W m^{-2})	14.9	41.8	15.1	7.1	17.1	22.9	20.7	5.6
Cotrib. to SEB (%)	18.7	66.8	61	134	2.5	2.8	16.8	7.2
Extra AR (%)	7.9	54.5	48.8	121.8	-7.9	-9	5.2	-3.9
Season	Fall				Winter			
AR Freq. (%)	10.6	12.4	12.5	11.8	10.5	12.3	12.7	12.4
Climatology (W m^{-2})	-25.3	-72.2	-9.1	18.1	-21.3	-96.2	11.2	23.8
Anomalies (W m^{-2})	20.8	48.6	10.4	7.4	17.5	62.1	5.6	10
Cotrib. to SEB (%)	4.3	7	16.3	17.3	2.5	4.8	16.4	28
Extra AR (%)	-6.3	-5.4	3.8	5.5	-8	-7.5	3.7	15.6

Table S1. Regional average results of Net Surface Longwave Radiation (LWN, top panel), Net Surface Shortwave Radiation (SWN, middle panel) and Turbulent Heat Flux (TH, bottom panel) across different seasons: Spring (shaded in green), Summer (shaded in orange), Fall (shaded in yellow), and Winter (shaded in blue). Results include AR occurrence frequency (AR Freq., unit: %), Climatology (unit: W m^{-2}), composite anomalies (unit: W m^{-2}), total AR contribution to absolute net SEB (Contrib. to SEB, unit: %), and relative AR contribution to the net SEB compared to the AR frequency (Extra AR, unit: %).

Surface Temperature								
Region	Central Arctic	Subpolar Oceans	Continents	Greenland	Central Arctic	Subpolar Oceans	Continents	Greenland
Season	Spring				Summer			
AR Freq. (%)	10.8	12.3	12.2	12.2	10.4	11.8	11.6	11.1
Climatology (K)	259.8	269.4	263.6	250.3	274.2	278.4	284	266.4
Anomalies (K)	4	2.1	5.2	6.4	0.1	0	1.1	2.8
Season	Fall				Winter			
AR Freq. (%)	10.6	12.4	12.5	11.8	10.5	12.3	12.7	12.4
Climatology (K)	264.7	274.9	265.4	251.6	252.3	265.9	247.5	242.4
Anomalies (K)	3.1	1.1	5.4	7	6.2	3.2	9.5	8.6
T-2m Air Temperature								
Region	Central Arctic	Subpolar Oceans	Continent	Greenland	Central Arctic	Subpolar Oceans	Continents	Greenland
Season	Spring				Summer			
AR Freq. (%)	10.8	12.3	12.2	12.2	10.4	11.8	11.6	11.1
Climatology (K)	259.5	268.2	264.3	253	274.5	278.6	283.8	267.9
Anomalies (K)	4.5	3.5	5.7	6.5	0.8	0.9	1.7	2.9
Season	Fall				Winter			
AR Freq. (%)	10.6	12.4	12.5	11.8	10.5	12.3	12.7	12.4
Climatology (K)	264	273.4	266.2	254.9	251.8	263.8	249	246.5
Anomalies (K)	4	2.8	5.6	6.7	6.8	5.2	9.4	8.3

Table S2. Regional average results of Surface Temperature (top panel) and T-2m Air Temperature (bottom panel) across different seasons: Spring (shaded in green), Summer (shaded in orange), Fall (shaded in yellow), and Winter (shaded in blue). Results include AR occurrence frequency (AR Freq., unit: %), Climatology (unit: K), composite anomalies (unit: K).

Surface Downward Longwave Radiation (LWD)								
Region	Central Arctic	Subpolar Oceans	Continents	Greenland	Central Arctic	Subpolar Oceans	Continents	Greenland
Season	Spring				Summer			
AR Freq. (%)	1.7	5.5	3.1	2.1	7.7	8.6	8.3	5.4
Anomalies (W m^{-2})	40.8	43.6	44.2	61.5	13.7	22	22.5	37.9
Cotrib. to SEB (%)	7.2	39.4	78.7	373	1.6	1.9	13	54.5
Extra AR (%)	5.5	33.9	75.6	370.9	-6.1	-6.7	4.7	49.1
Season	Fall				Winter			
AR Freq. (%)	3.1	7.4	4.9	3.4	1.3	6	2.3	1.6
Anomalies (W m^{-2})	31.1	38.1	38.2	60.4	73.4	59.9	65.9	76.8
Cotrib. to SEB (%)	2.2	3.4	22.6	34.7	1.2	2	32.7	16.6
Extra AR (%)	-0.9	-4	17.7	31.3	-0.1	-4	30.4	15

Table S3. According to M23 AR index, regional average results of AR occurrence frequency (AR Freq., unit: %), composite anomalies of Surface Downward Longwave Radiation (LWD) during AR events (Anomalies, unit: W m^{-2}), total AR contribution to absolute net SEB (Contrib. to SEB, unit: %), and relative AR contribution to the net SEB compared to the AR frequency (Extra AR, unit: %) across different seasons: Spring (shaded in green), Summer (shaded in orange), Fall (shaded in yellow), and Winter (shaded in blue).