4.8. CONTEMPORARY CLIMATE CHANGES IN HIGH LATITUDES OF THE NORTHERN HEMISPHERE: DAILY TIME RESOLUTION

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1. Introduction

Significant climatic changes over the high latitudes in the 20th century have been reflected in many atmospheric, oceanic, and terrestrial variables. While changes in surface air temperature and precipitation are most commonly addressed in the literature (cf., Appendix 2; Karl 1998; Lugina et al. 2001), changes in their derived variables (variables of economic, social and ecological interest based upon daily temperatures and precipitation) have received less attention. The list of these variables (indices) being considered in this paper includes:

- frequency of extremes in precipitation and temperature;
- frequency of thaws;
- heating degree days;
- growing season duration;
- sum of temperatures above/below a given threshold;
- days without frost;
- day-to-day temperature variability;
- precipitation frequency;
- precipitation type fraction;
- frequency of rain-on-snow events; and
- Keetch-Byram (Soil Moisture) Drought Index (KBDI; Keetch-Byram 1968).

In practice, these and other indices are often used instead of "raw" temperature and precipitation values for numerous applications that include modeling of crop-yields, prediction and planning for pest management, plant-species development, greenhouse operations, food-processing, heat oil consumption in remote locations, electricity sales, heating system design, power plant construction, energy distribution, reservoir operations, floods and forest fires. These indices provide measure for the analysis of changes that might impact agriculture, energy, and ecological aspects of high latitudes over the past 50 years.

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2. Data

We performed our analysis for the 1950-2000 period using a subset of about 1500 stations north of 50ºN from the recently created Global Daily Climatology Network archive (GDCN, Gleason et al. 2002; Figure 1). When considering temperature variations over Canada within this data set for 210 Canadian stations with homogenized temperature time series (Vincent and Gullett 1999), a priority was given to these high-quality data instead of the observations in the GDCN. Precipitation time series for the former

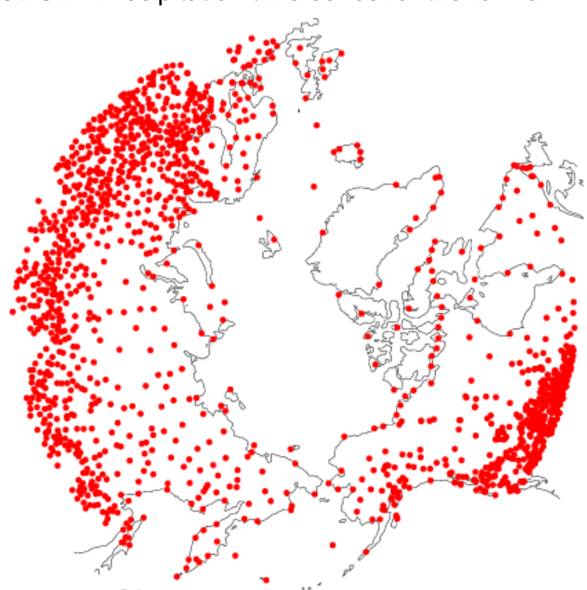

Figure 1. Map of GDCN stations north of 50°N with more than 25 years of valid daily data.

USSR (fUSSR) and Canada were homogenized to account for changes in instrumentation and observational practice as described in Groisman and Rankova (2001) and NCDC (1998). It should be noted that precipitation time series in high latitudes are biased due to the difficulty of making accurate solid precipitation measurements. A comprehensive correction of these measurements, similar to those suggested by Bogdanova et al. (2002) and/or Mekis and Hogg (1999), requires supplementary information (first of all, wind speed at the gauge level) that was not readily available and has not been completed at this stage of analysis. Instead, we used instrumentally-homogenized but biased precipitation time series and present the results in a "non-dimensional" form (percent, days above thresholds based on distribution of these time series, etc.) This shortcoming is potentially dangerous because in regions of rapid temperature change, observed variations in measured precipitation can be modulated by changes of the measurement bias of frozen versus liquid precipitation (Førland and Hanssen-Bauer 2000).

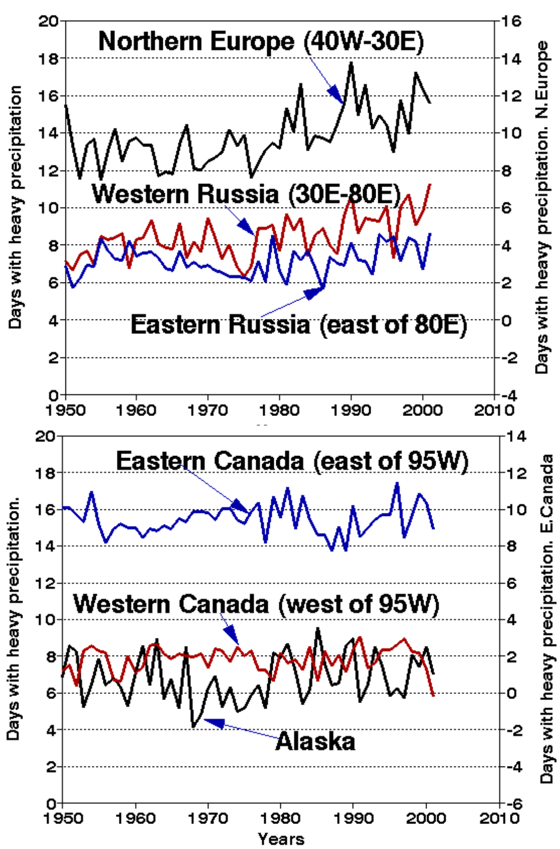

Figure 2. Annual number of days with "heavy" precipitation events defined as those above two standard deviations of the "non-nonsense" events, σ, NHP. Because the numbers of wet days are different among the regions, mean NHP varies between humid and dry regions of the high latitudes. Averaging routine used here and throughout this section is described in Appendix 1.

3. Results

3.1. Frequency of extreme events

To define ***"heavy" precipitation*** events in Figure **2**, an upper monthly fraction (> 2σ) of precipitation events over 0.5 mm ("non-nonsense" precipitation events) is used. σ is estimated using maximum likelihood estimates of gamma-distribution for each month during the 1961-1990 reference period. This approach picks up "unusual" precipitation events throughout the year rather than concentrating on the most humid season (summer over most of the Arctic). Figure **2** shows a general increase (by 12% per 50 yrs) of the frequency of annual heavy precipitation events, but all of this increase comes from Eurasia while in North America changes are insignificant.

Unusually cold and/or warm days affect the "usual" cycle of the Arctic ecosystem and numerous human activities. Figure **3** depicts what has happened during the past fifty years with this

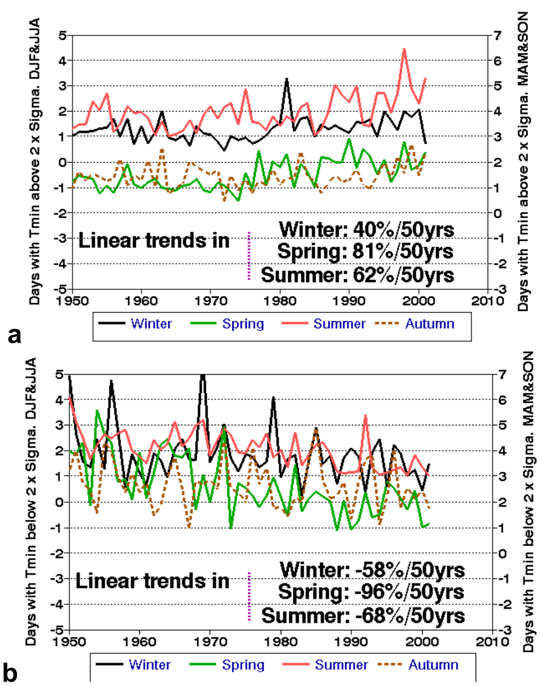

Figure 3. Seasonal number of unusually *(a)* warm and *(b)* cold nights (i.e., above/below the mean monthly values of T_{min} by more than two standard deviations for each month) area-averaged over high latitudes north of 50ºN (Alaska, Canada, Fennoscandia, and the former USSR).

frequency in the nighttime in the high latitudes using minimum temperature (T_{min}) observations. Similar changes but with a smaller amplitude were observed in the daytime (using maximum temperature observations). A significant (a twofold in spring) decrease in very cold nights over the Arctic is observed in winter, spring, and summer but not in autumn.

3.2. Thaw days

A day with thaw (snowmelt) can be defined as a day with snow on the ground when the daily mean temperature is above –2ºC (Brown 2000). During these days snow deteriorates, changes its physical properties, and eventually disappears. In winter and early spring in high latitudes, thaws negatively affect transportation, winter crops, and sustainability of the natural environment, including vegetation and wild animals. In late spring, intensification of thaw conditions leads to earlier snow retreat and the onset of spring (Groisman et al. 1994; Brown 2000). Gradual snowmelt during

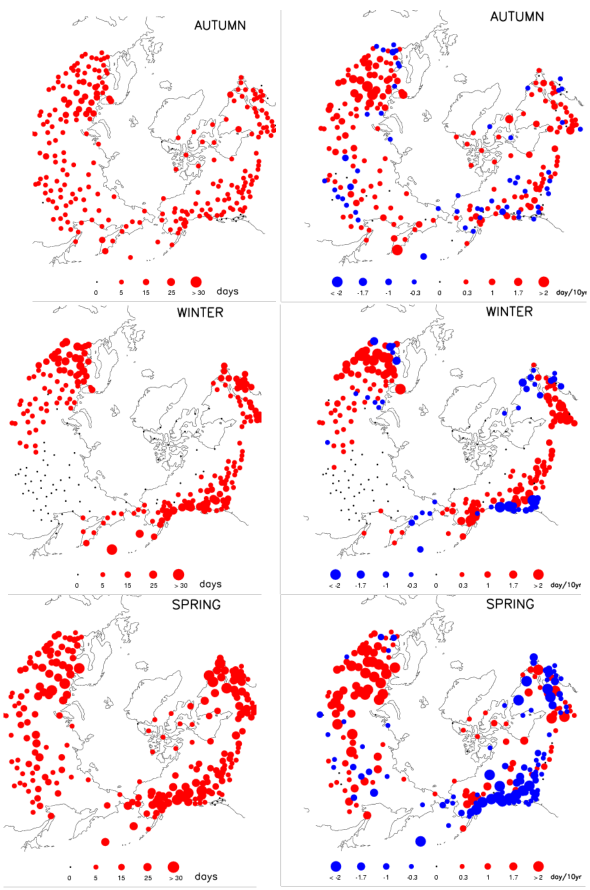

Figure 4. Thaw days over Alaska, Canada, and the former USSR; climatology & trends (blue denote negative trends).

the cold season affects seasonal runoff of the northern rivers, reducing the peak flow of snowmelt origin and increasing the mid-winter low flow. Figure **4** shows the climatology of thaws over North America and Russia and provides estimates of their change during the past fifty years. The time series in Figure **5** demonstrate statistically significant increasing trends for winter and autumn of 1.5 to 2 days per 50 years. This change constitutes a 20% (winter) to 40% (autumn) increase in the thaw frequency during the second half of the 20th century.

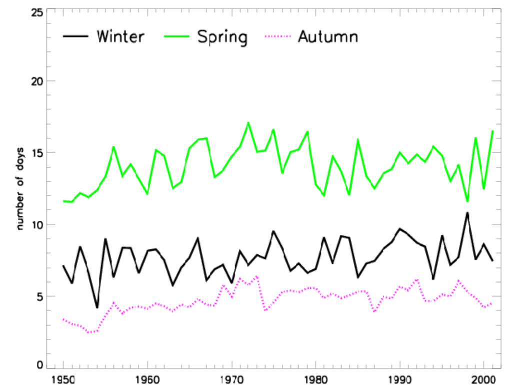

Figure 5. Circumpolar frequency of days with thaw area averaged over Alaska, Canada, and the fUSSR.

3.3. Heating degree-days, duration of growing season, and sum of temperatures above/below a given threshold.

Heating degree-days are the sum of positive mean daily temperature (T_{mean}) anomalies from the base temperature $(T_{base} - T_{mean})_+$. For calculations shown in Figure **6** we used T_{base} equal to 18º C (a compromise between 65ºF routinely used in the United States and 17 ºC used in Norway). Heating degree-days closely correlate to energy consumption for heating and have numerous other practical implications (Guttman and Lehman 1992). Figure **6** shows a statistically significant decrease in annual heating degree-days during the past 50 years of 6% per 50 years over the entire Arctic, with a maximum absolute and relative reduction in heating-degree days over western Canada and Alaska (of 9% and 8% per 50 years, respectively). In Eurasia, significant reductions in heating degree-days are observed over Russia (6% to 7% per 50 years). This indicates that there have been reduced heating costs in relative terms.

The duration of the growing season defined by the dates of steady (at least 5-day-long) transition of mean daily temperatures across +10°C is used to define "growing season" in the high latitudes. A

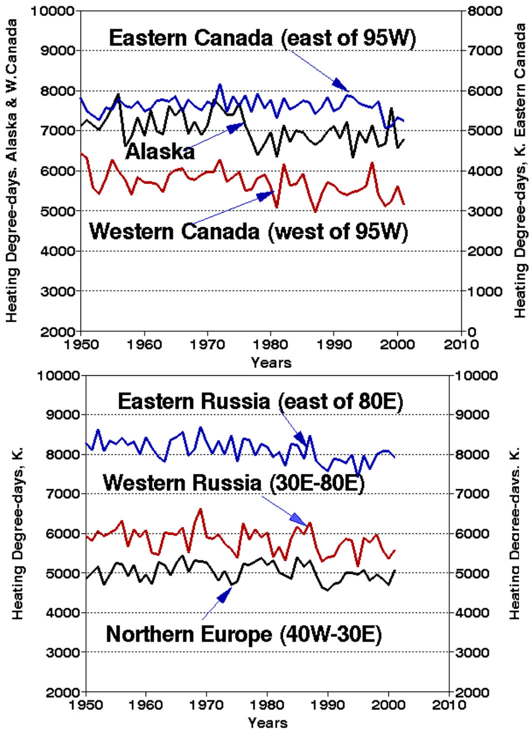

Figure 6. Annual number of heating degree-days area-averaged over Alaska, Canada, Northern Europe, and Russia north of 50ºN.

threshold of +10°C was selected to account for the continental climate of the Arctic where daily temperatures as high as 5°C can be accompanied by nighttime frost which is unfavorable for vegetation growth. Figure **7** shows climatology of the defined growing season and its changes during the past fifty years. The largest absolute and relative changes in duration of the growing season occurred over Alaska and western Canada (15 and 10 days or 19% and 8% per 50 years respectively). Another region of significant increase of the growing season duration is Russia (from 7 in the East to 10 days in the West, or 8% per 50 years). On average over the entire land area north of 50ºN, we found a 6% increase per 50 years in the duration of the growing season.

Sums of mean daily temperatures above certain thresholds (5°C, 10°C, or 15° C) are used in bio- and agro-climatology to define the northernmost limits of expansion of different vegetation species including crops. The ongoing warming of the high latitudes causes shifts in these sums and, therefore, creates a potential to change the boundaries. Figure **8** provides regional changes of the sums with mean daily temperature above 15° C (the tendencies for positive sums above two other thresholds are similar). Figure **8** shows a

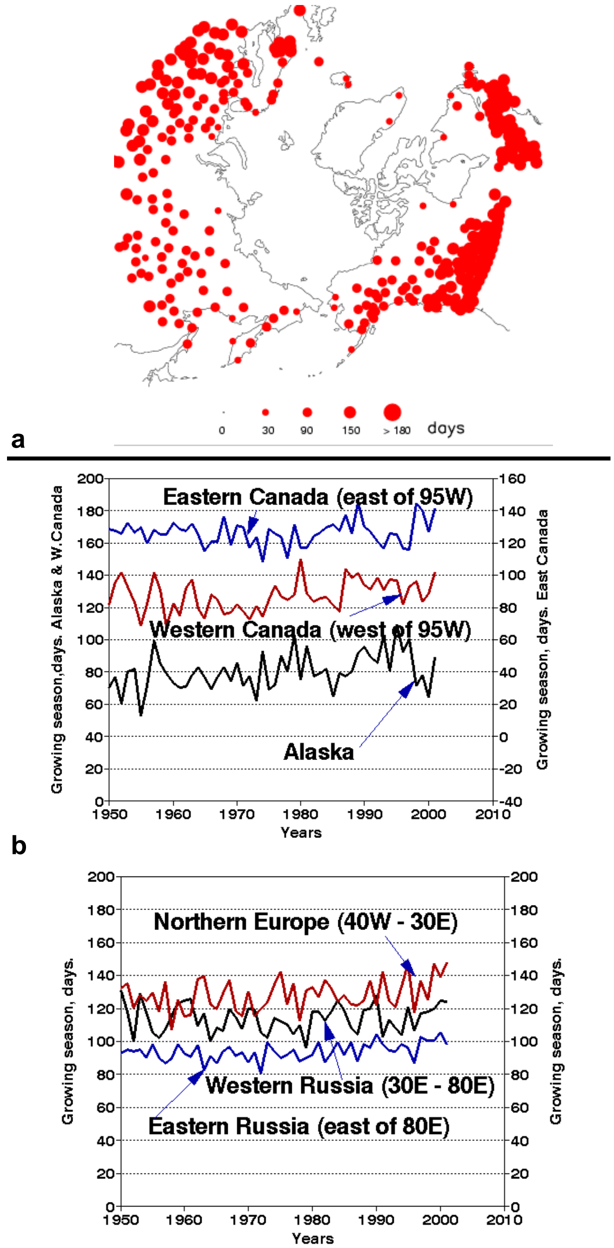

Figure 7. Duration of the growing season (period with mean daily temperatures above 10º C) in the high latitudes of the Northern Hemisphere (*a*) climatology and (*b*) regional changes.

12% per 50 years increase over the entire Arctic (with the strongest increases over North America and Siberia). This result supports the increase in “greenness” of the high latitudes (reported recently from satellites; Myneni et al. 1997), provides a longer time scale (compared to the remote sensing results), and quantifies the “greenness” changes.

To characterize the severity of the cold season, a sum of negative temperatures can be used. Time series of this characteristic for winter (Figure

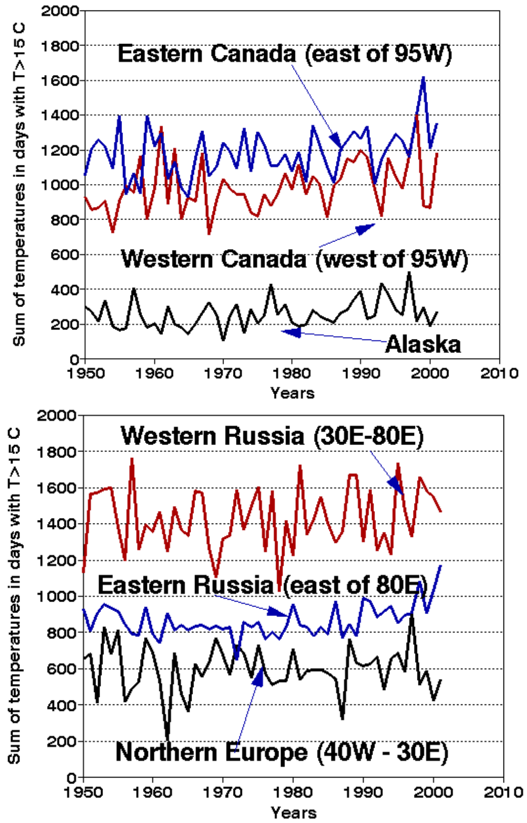

Figure 8. Regional changes of sums of mean daily temperatures above 15°C over Alaska, Canada, Northern Europe, and Russia north of 50ºN.

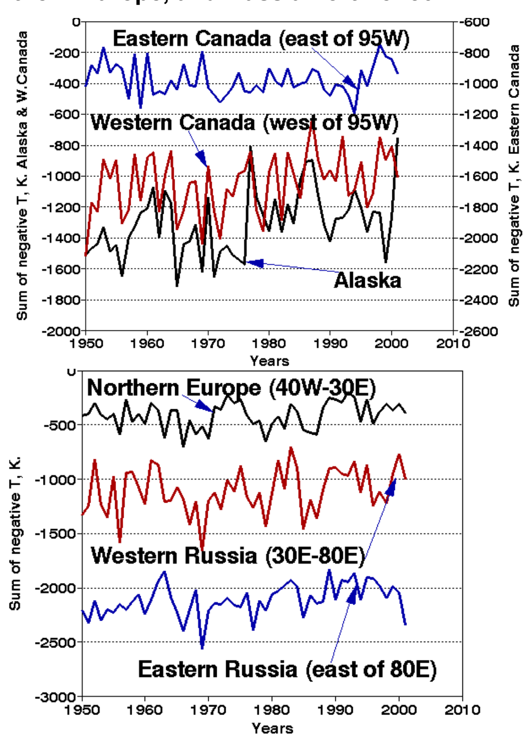

Figure 9. Regional changes over Alaska, Canada, Northern Europe, and Russia north of 50ºN of sums of mean daily winter (DJF) temperatures below 0°C.

9) and for the entire cold season (not shown) indicate that the annual "severity" of the cold season has substantially decreased everywhere except eastern Canada. The mean circumpolar decrease is 13% per 50 years (in absolute value of negative temperature sums).

3.3. Days without frost

The length of the frost-free period is among the most carefully monitored variables in the Arctic.

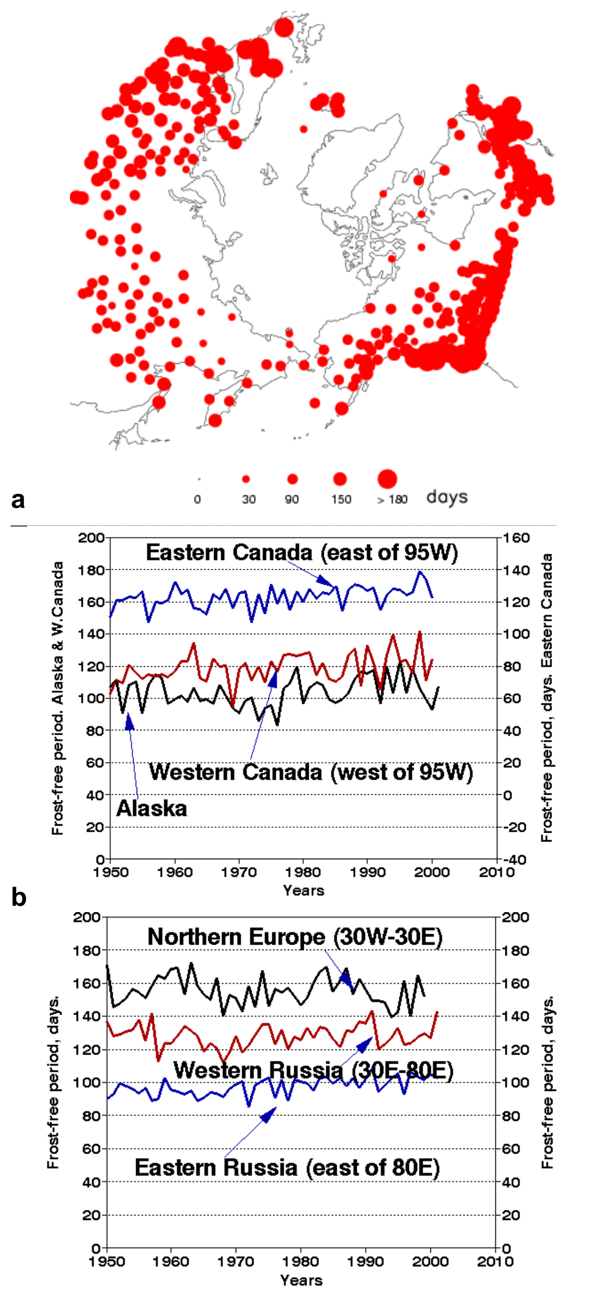

Figure 10. Duration of the period without frost (period with minimum temperatures above 0º C) in the high latitudes of the Northern Hemisphere (a) climatology and (b) regional trends.

Figure **10** provides climatology and regional trends for this variable. The regionally averaged duration of the frost-free period varies from less then 100 days in Alaska to more than 150 days in Fennoscandia and has increased (by 7% per 50 years) over most of the Arctic except Europe. It is interesting to note the increase in the frost-free period in Eastern Canada (by 8% per 50 years, or by 9 days) where the duration of growing season changed insignificantly.

3.5. Day-to-day temperature variability

The very high day-to-day temperature variability affects the quality of living in the high latitudes, causing a variety of transportation and health problems and requiring additional construction expenditures. Figure **11** depicts major seasonal tendencies in this variability during the past fifty years. It shows a decrease in day-to-day mean square root variability of daily temperature in all seasons. In spring and summer seasons this decrease (about 7% per 50 years) is statistically significant at the 0.01 level.

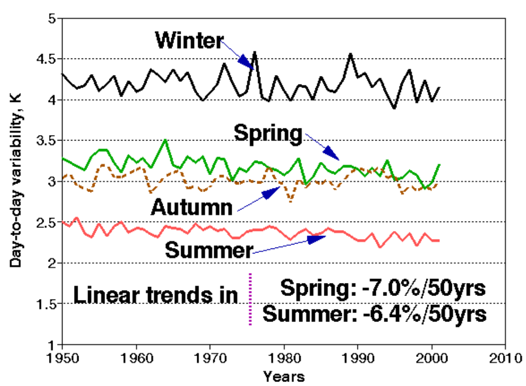

Figure 11. Seasonal variations in the day-to-day temperature variability area-averaged over Alaska, Canada, Northern Europe, and Russia north of 50ºN.

3.6. Precipitation frequency

Reporting changes in precipitation frequency in the Arctic is not a trivial task due to a significant fraction of very light precipitation events (e.g., traces) comparable to the gauge precision. To avoid uncertainties with measurement of ephemeric amounts of precipitation and instability with time of precision of their reporting, we assessed a climatology and trends of annual number of days with precipitation above 0.5 mm (Figure **12**). Figure **12** shows insignificant changes in wet days over North America, Northern Europe, and western Russia and a significant decrease in wet days over eastern Russia by 7 days (~7%) per 50 years. This last feature was first reported by Sun et al (2001) for eastern Russia south of 60°N and is remarkable because it is accompanied by an increase in heavy precipitation in the same region (Figure **2**).

3.7. Liquid and frozen precipitation

Karl (1998) reported a century-long increase in high-latitudinal precipitation that is reproduced also by contemporary GCMs (Kattsov and Walsh 2000). Below we examine these changes in both frozen and liquid forms. For the land regions north of 50°N, rainfall contributes about three

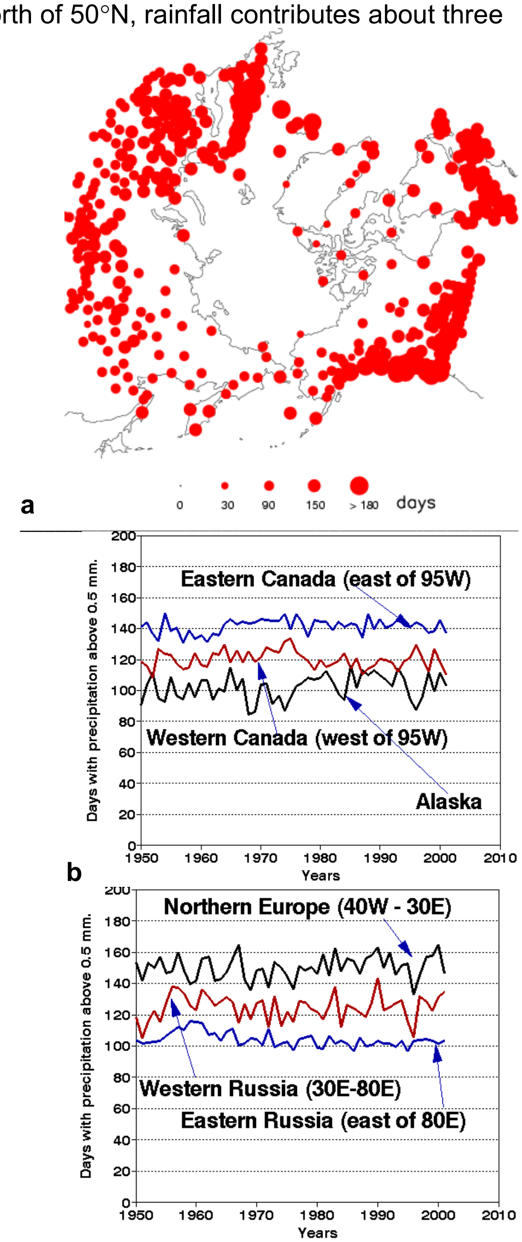

Figure 12. (a) Climatology of mean annual number of days with precipitation (above 0.5 mm) and (b) its regional variations.

quarters of the annual precipitation total. Figure **13** presents its regional variations. In Eurasia, temperature criterion was used to partition frozen and liquid forms of precipitation measurements while direct snowfall measurements were available for North America. Figure **13** shows a significant (6% per 50 years) circumpolar increase in annual rainfall. This increase is partially due to an additional fraction of liquid precipitation in the intermediate seasons. Groisman and Easterling (1994) and Mekis and Hogg (1999) reported an increase in annual snowfall north of 55°N over North America.

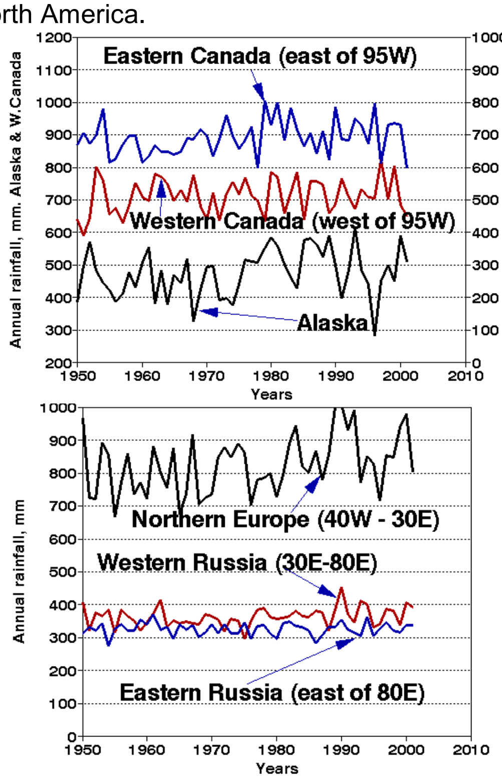

Figure 13. Mean annual rainfall area-averaged over Alaska, Canada, Northern Europe, and Russia north of 50ºN.

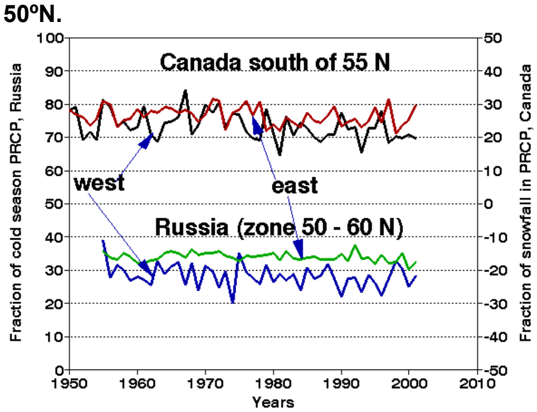

Figure 14. Mean annual fraction of frozen precipitation (snowfall) area-averaged over Canada south of 55°N and Russia within the 50°N to 60°N latitudinal belt.

However, a significant redistribution between liquid and frozen forms of precipitation has occurred in the humid southern parts of the Arctic south of 55°N in North America and south of 60°N in Eurasia (since the mid-1950s) [Figure **14**]. Thus, while cold season precipitation increased over most of the high latitudes its frozen component has not notably changed.

3.8. Rain-on-snow events

Rain falling on snow causes more rapid snowmelt and, when the rainfall is intense, may result in

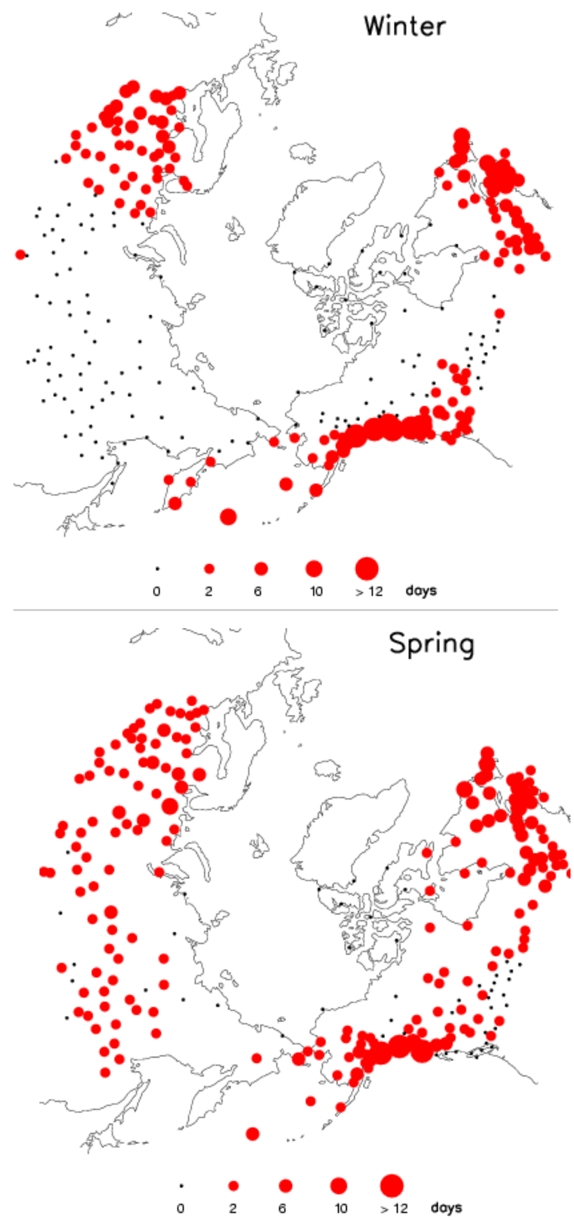

Figure 15. Climatology of winter and spring rain-on-snow events (number of days with rainfall ≥ 1 mm when snow on the ground is ≥ 3 cm).

flash flooding. Along the western coast of North America rain-on-snow events is the major cause of severe flash floods. Figures **15** and **16** show the frequencies of the rain-on-snow events over northern North America and Russia and their changes during the past fifty years. At this stage, a formal criterion was used to define these events: number of days with rainfall ≥ 1 mm when snow depth is ≥ 3 cm without accounting for ripening of the snowpack. Figure 16 shows a significant increase in the frequency of rain-on-snow events (*as defined above*) in winter over western Russia (by 50% per 50 years) and a significant reduction of similar size over western Canada. In spring, there is a significant increase of rain-on-snow events over Russia (mostly over its western part), but there is also a significant decrease of the frequency of these events in the western Canada. This decrease is mostly due to snow cover retreat.

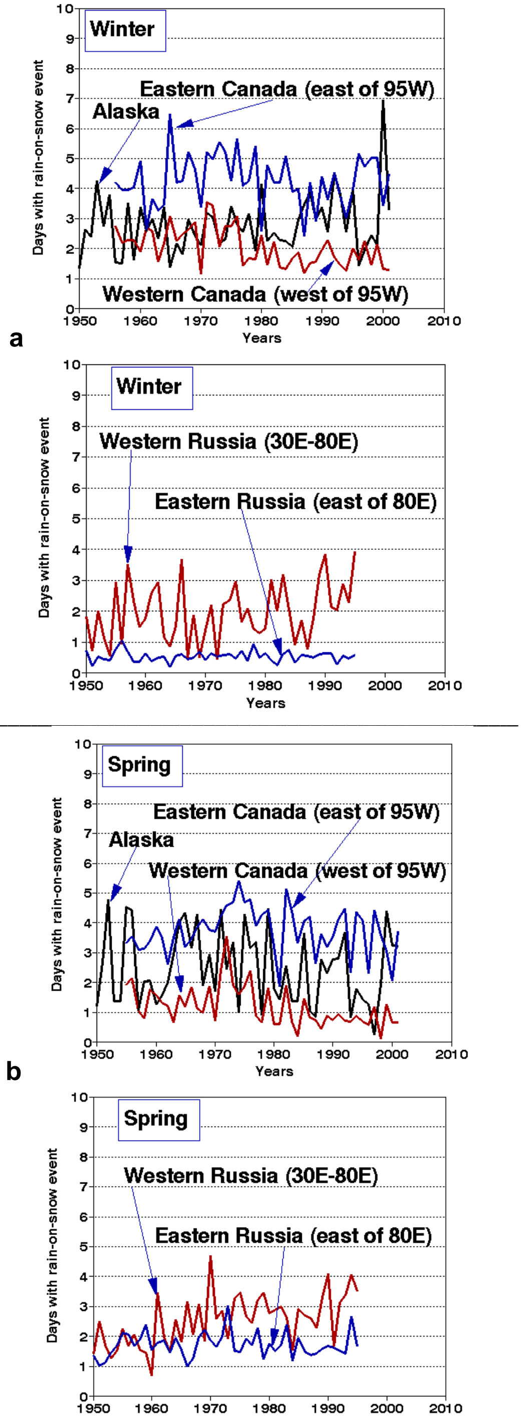

Figure 16. Regional variations of rain-on-snow events in (a) winter and (b) spring.

3.9. Keetch-Byram Drought Index

Each summer, forest and tundra suffer from numerous naturally caused fires that are difficult to fight due to the difficulty of reaching. To characterize the level of potential fire danger, numerous indices have been suggested. Among these indices, the Keetch-Byram Drought Index (KBDI; Keetch and Byram 1968) uses only daily temperature and precipitation information and estimates soil moisture deficiency on a scale ranging from 0 to 800 (zero is the point of no moisture deficiency and 800 is the most severe drought that is possible). The logic behind the index is that wet soil suppresses wild fires while dry soil organic matter enhances these fires and makes them difficult to control. In Figures **17** and **18**, the index is calculated for high latitudinal stations with daily temperature and precipitation available in GDCN for the past fifty years. Figure **18** shows that dryer soil conditions have

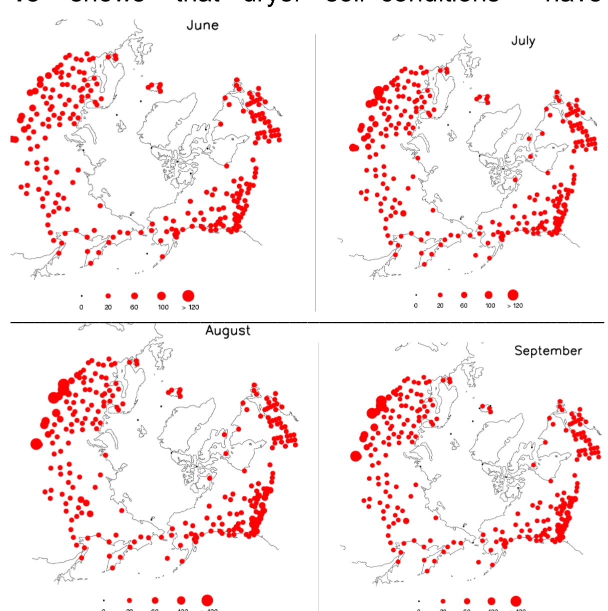

Figure 17. (a) KBDI climatology for the warm season (June-September).

increased slightly in Russia and central Canada but decreased over southeast and southwest of Canada. The drought danger in southern Russia and Canadian Prairies (frequency of the days with KBDI > 200, not shown) has decreased in August-September.

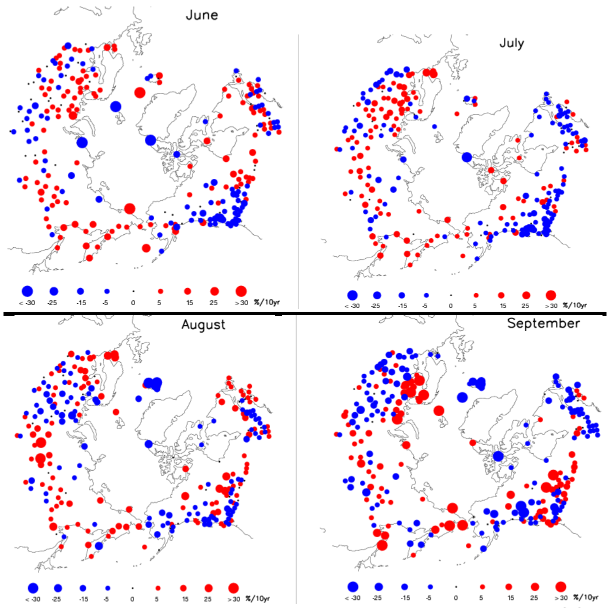

Figure 18. KBDI linear trends during the past fifty years (percent per 10 years). Red indicates positive trend values and blue negative values. KBDI values above 100 and 200 characterize drought stages 1 and 2 respectively (Keetch and Byram 1968).

4. Summary

In the previous section we have presented information about changes of nine climatic derivatives with economic, social and ecological implications over the high latitudes of the Northern Hemisphere during the past fifty years. These changes imply increases and decreases in risk. Whatever "implications" would be assigned to these observed changes, it is important to note that many of them have been significant enough to be noticed above the usual "weather" noise level during the past fifty years and thus should be further investigated in order to better understand and adapt to their impacts.

5. References

Bogdanova, E.G, Ilyin, B.M., and Dragomilova, I.V. 2002: Application of a comprehensive bias correction model to precipitation measured at Russian North Pole drifting stations. *J. Hydrometeorol*. (in press).

Brown, R.D., 2000: Northern Hemisphere snow cover variability and change, 1915-1997, *J. Climate*, **13**, 2339-2355.

Easterling, D.R., T.R. Karl, E.H. Mason, P.Y. Hughes, D.R. Bowman, R.C. Daniels, and T.A. Boden, 1996: United States Historical Climatology Network (U.S. HCN). Monthly temperature and precipitation data. ESD Publ. 4500, ORNL/CDIAC/-87, NDP-019/R3. Prepared and available from Carbon Dioxide information Analysis Center, Oak Ridge National Lab., Oak Ridge, Tennessee, 37831-6335. 83 pp.

Førland, E.J., and I. Hanssen-Bauer, 2000: Increased precipitation in the Norwegian Arctic: True or False? *Climatic Change*, **46**, 485-509.

Gleason, B. E., T.C. Peterson, P.Ya. Groisman, D.R. Easterling, R.S. Vose, and D.S. Ezell, 2002: A new global daily temperature and precipitation data set. Presented at the 13th AMS Symposium On Global Change Studies, Orlando, FL, 13-17 January, 2002.

Groisman, P.Y. and D.R. Easterling, 1994: Variability and trends of precipitation and snowfall over the eastern United States and Canada, *J. Climate*, **7**, 184-205.

Groisman, P.Ya. and E. Ya. Rankova, 2001: Precipitation trends over the Russian permafrost-free zone: removing the artifacts of pre-processing. *Internat. J. Climatol.* **21**, 657-678.

Groisman, P. Ya., T.R. Karl and T.W. Knight, 1994: Observed impact of snow cover on the heat balance and the rise of continental spring temperatures, *Science*, **263**, 198-200.

Groisman, P.Ya. R.W. Knight , and T.R. Karl, 2001: Heavy precipitation and high streamflow in the contiguous United States: Trends in the 20th century. *Bull. Amer. Meteorol. Soc*., **82**, 219-246.

Guttman, N.B. and R.L. Lehman, 1992: Estimation of daily degree-days. *J. Appl. Meteorol*., **31**, 797-810.

Kagan, R.L., 1997: *Averaging of meteorological fields*, Kluwer Academic Publishers, 279 pp.

Karl, 1998: Regional trends and variations of temperature and precipitation. *The regional Impacts of Climate Change: An assessment of Vulnerability*. R.T. Watson, M.C. Zinyowera, R.H. Moss, and D.J. Dokken, Eds., Intergovernmental Panel on Climate Change, Cambridge University Press, 412-425.

Kattsov, V. M., and J. E. Walsh, 2000: Twentieth-century trends of Arctic precipitation from observational data and a climate model simulation. *J. Climate.,* **13**, 1362–1370

Keetch, J.J. and G.M. Byram, 1968: A drought index for forest fire control. U.S.D.A. Forest Service Research Paper SE-38. 35 pp. [Available from: http://www.srs.fs.fed.us/pubs/]

Lugina, K.M. P.Ya. Groisman, K.Ya. Vinnikov, V.V. Koknaeva, and N.A. Speranskaya, 2001: Monthly surface air temperature time series area-averaged over the 30-degree latitudinal belts of the globe, 1881-1999. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA.

Mekis, E. and W.D. Hogg, 1999: Rehabilitation and analysis of Canadian daily precipitation time series, *Atmosphere-Ocean*, **37**, 53-85.

Myneni R.B, Keeling C.D, Tucker C.J, Asrar A., Nemani R.R. 1997: Increased plant growth in the northern high latitudes from 1981-1991. *Nature,* **386**, 698-702.

National Climatic Data Center (NCDC), 1998: Data Documentation For Archive TD-9816, Canadian Monthly Precipitation, November 18, 1998. 21 pp. [Available from http://lwf.ncdc.noaa.gov/oa/ncdc.html].

Sun, B., Groisman, P.Ya., and I. I. Mokhov, 2001: Recent changes in cloud type frequency and inferred increases in convection over the United States and the former USSR. *J. Climate* **14**, 1864-1880.

Vincent, L.A., and D. W. Gullett, 1999: Canadian historical and homogeneous temperature datasets for climate change analyses. *Int. J. Climatol.*, **19**, 1375-1388.

Appendix 1. Description of the area-averaging routine.

1. Throughout Section 3, area-averaging was performed as follows: First station data anomalies from the long-term mean for the reference 1961-1990 period (or statistics) were averaged within each 1° x 2° gridcells. These averaged grid cell values are presented in “bubble” maps in Figures 4, 7, 10a, 12a, 15a, and 16. The gridcell values (those with at least 1 valid station value within) were then averaged further over the region with weights proportional to the gridcell latitude. This approach does not pretend to cover the entire region. The focus was on the data-elucidated regions where people live and maintain meteorological observations for sufficiently long periods of time because most climatic characteristics studied here directly affect, for better or worse, the health and well-being of human settlements.

2. Seven regions north of 50°N (except Canada, which was included in its entirety) were selected for averaging: Alaska (west of 141°W), western Canada (west of 95°W but including the southern coast of Alaska east of 141°W), eastern Canada (east of 95°W but including Greenland west of 40°W), Northern Europe (sector north of 55°N, between 40°W and 30°E), northwestern Russia (sector north of 50°N, between 30° and 80°E), and eastern Russia (Siberia; east of 80°E and north of 50°N). On one occasion (in Figure 14), only the southernmost portion of western and eastern Canada (south of 55°N) and western and eastern Russia within the 50°N to 60°N latitudinal belt were considered.

Appendix 2. Temperature changes in high latitudes.

This appendix summarizes our current knowledge about the contemporary temperature changes in the high latitudes. The temperature increase in the high latitudes of more than 1ºK (more than 2ºK in winter) during the 20th century was not monotonic (Figure **A1**). A one and half degree increase in annual temperatures during the 1920-1940 period was followed by a similar size decrease up to the early 1960s with monotonic increase thereafter. Currently, the high-latitudinal temperatures are close to those observed at the peak of the Arctic warming in the end of 1930s and exceed those in the summer season. Figure **A2** shows an all-season all-latitudes warming in the northern extratropic land area during the past several decades that leaves only small western fractions of the North Atlantic and North Pacific to manifest the circulation peculiarities of global warming in the winter season.

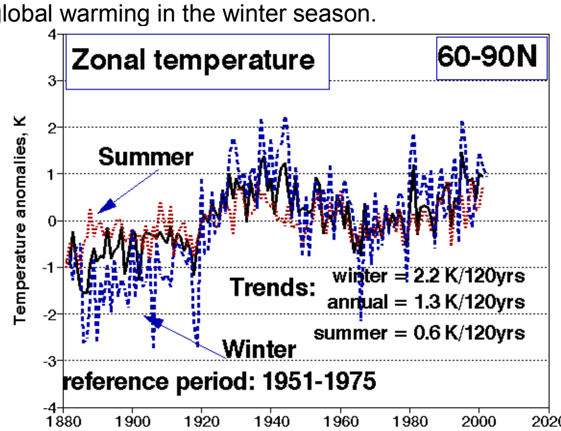

Figure A1. Arctic zonal (within 60º-90º N latitudinal zone) temperature anomalies during the 1881-2001 period. Winter (blue), summer (red), and annual (black) anomalies are presented (Lugina et al. 2001, updated). All linear trends are statistically significant at the 0.01 level. The time series were calculated using optimal averaging with normalized weights technique (Kagan 1997).

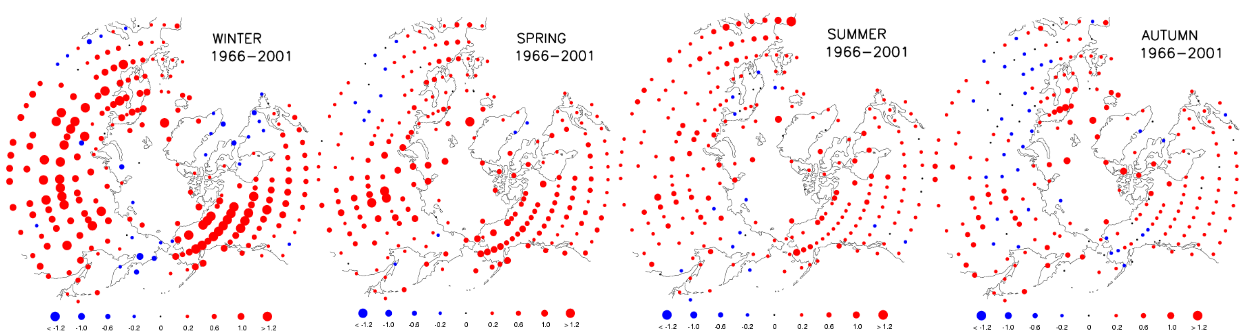

Figure A2. Seasonal temperature trends for period of the latest Arctic warming (1966-2001). Trends are presented in K/10yrs with following conventions: red color indicates positive trend values and blue – negative values. The dot size is proportional to the trend magnitude: with the largest dots indicate trends exceeding 2.5K/10years (Data sources: Easterling et al. [1996] and Vincent and Gullett [1999] both updated to 2001).