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Long-term climate trends of the Yamalo-Nenets AO, Russia

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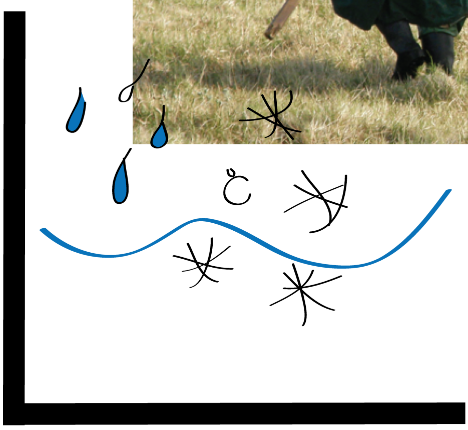

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Abstract

See next page.

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Snow, temperature, precipitation, Yamalo-Nenets AO, Sibiria, Russia

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Abstract

In this study trends and variability of temperature, precipitation and snow at four stations of the Yamalo-Nenets AO, Russia (Mare-Sale, Tarko-Sale, Salekhard and Nadym) were examined along a simulated migration gradient used by nomadic reindeer herders where Mare-Sale represents pastures used in summer and the Nadym region is used during winter. Migration between summer and winter pastures can be as long as 1500 km in one direction. Several climate parameters were chosen for analysis: annual and seasonal temperature, annual and seasonal precipitation sum, maximum snow depth, snow season duration, rain-on-snow events and cold periods.

The covariance between temperature series from all four stations is high. Average seasonal temperature cycles are also similar (from about -25°C in January to +15°C in July), with the exception that Mare-Sale is considerably cooler than the other stations in spring and summer and slightly milder in winter. The long-term trend is investigated at Salekard. The spring temperature shows a significant positive trend of almost 0.2°C per decade from 1900 to 2008. For the other seasons, the temperature shows no statistically significant long-term trends. All series show warm periods in the 1940s and 1990s, and a cold period in the 1960s. Salekard (the only station with observations at that time) was cold also around 1900. All series indicate a warming from the period 1961-1990 to 1979-2008. In Mare-Sale the warming was largest during autumn (0.9°C). At the other stations, it was largest (>1°C) in spring.

Also for precipitation, the average seasonal cycle is similar at Tarko-Sale, Salekhard and Nadym. February has the lowest monthly precipitation average (<20 mm) while the highest values (60-70 mm) are found in July and August. In Mare-Sale the precipitation values are in general lower, especially in summer, and the lowest monthly average is found in March while the highest is in September. The covariance between the series from the four stations is considerably lower for precipitation than for temperature, however there tend to be positive trends at all stations. The long-term trend was investigated at Salekard, and statistically significant increase was found in all seasons from 1900 to 2008. The annual trend amounts to 33% in 100 years. Some of this increase may be caused by possible inhomogeneities. All stations show increased annual precipitation from the period 1961-1990 to 1979-2008.

Variability in length of the snow season was studied mainly at Mare-Sale and Salekard. Both series show a considerable (2-3 weeks) reduction in the snow season from the 1930s to the 1940s, followed by an even larger increase (3-4 weeks) to the 1960s. The snow season was rather long at both stations up to the early 1980s. Then Salekard experienced a considerable and persistent reduction in the snow season, mainly because of earlier melting in the spring, while the snow season at Mare-Sale after a short drop again was prolonged. The reason for this difference may be differences in the precipitation patterns, but it is probably also caused by differences in the effect of the spring-time temperature increase: In Salekard, the average May temperature 1961-1990 was -2°C, and the spring warming probably increased the potential for snow melt considerably. In Mare-Sale, May is at average 4°C colder than in Salekard, and the temperature increase thus had less influence on the snow melt.

The differences between Mare-Sale and the other stations concerning temperature and precipitation are partly caused by differences in maritime influence. The variability in sea-ice conditions in the Kara Sea is affecting the maritime influence in Mare-Sale. More detailed data and analyses will be needed to study the connection between sea ice conditions and the climate of this area.

Contents

1 Introduction

This report has been written as part of the IPY project EALAT-RESEARCH: “Reindeer Herders Vulnerability Network Study: Reindeer pastoralism in a changing climate” (http://icr.arcticportal.org/en/ealat). Furthermore, this study is also a part of the Arctic Council project EALAT Information: “Reindeer herders voice, reindeer herding and adaptation to climate change and loss og grazing land”. The presented study is part of the Work Package 1: *Identification of local climate conditions important for reindeer herding and development of basic climate scenarios.* The main goal of the entire EALAT project is to assess the vulnerability of reindeer herding to effects of climate change in Finnmark, Northern Norway and in the Yamalo-Nenets AO (Autonomous Okrug), an administrative division of Tyumen, North-western Sibiria, Russia. This report contributes to reach the main goal by describing the historical climate on the Yamalo-Nenets AO the last 100 years, from the coast to the inland areas. The historical climate at Finmarksvidda, Northern-Norway is described in Vikhamar-Schuler et al. (2010).

We present historical climate data from Yamal (four selected meteorological stations). Long-term trends of temperature, precipitation and snow are studied. Additionally, some meteorological parameters (indices) have been computed that are sensitive to the reindeers access to food through the snow. The climate conditions affect the reindeer herding in many ways, but we have chosen to limit our study to indices affecting the food access through the snow. Examples of such indices are rain-on-snow events followed by freezing temperatures possibly creating hard ice layers. Ice layers are negative for the reindeer since they prevent the animals to reach the food below the snow. On the other hand, loose snow structures (depth hoar crystals) increase the accessibility of food below the snow pack. Depth hoar forms preferentially in cold, continental type climate. Therefore, we also examined a cold period indice based on degree days for temperatures below 0 °C, -15 °C and -30°C.

Figure 1: Yamalo-Nenets AO is located in northwestern Siberia.

2 The Yamal peninsula and the Yamalo-Nenets AO

The Yamal peninsula is located within the Yamalo-Nenets AO, an administrative division of Tyumen, North-West Sibiria, Russia (Figure 1). On the west coast is the Kara sea, while the gulf of the river Ob is on the east coast of the Yamal peninsula. The peninsula consists of permafrost tundra (permanently frozen soil without growing trees). During the summer, temperatures rise and the top layer of the permafrost melts. This leaves the ground very wet and the tundra is covered in marshes and lakes. The Yamal peninsula comprised of rivers, lakes and permafrost only 180 meters abowe sea level, makes it vulnerable to future climate change.

The Yamal peninsula has 500 000 inhabitants and the administrative center is Salekhard (approx. 37 000 inhabitants). The Nenets people are an indigenous tribe that have long survived in this region. Many of them are living from traditional reindeer husbandery. 63% of the population at Yamal are Russians while the Nenets today constitute 4% of the population. Today there are about 300 000 reindeers on the Yamal peninsula (Forbes et al., 2009).

Reindeer husbandry in Yamalo-Nenets AO is a family based reindeer husbandry, a tight coupled human ecological system. Nenets, Khanti and Komi nomadic reindeer herders migrate as long as 1500 km in one direction from the Nadym area in winter to the western coast of northern Yamal Peninsula in summer (Mare-Sale), migrating with reindeer and families to new pasture land almost everyday.

The Yamal region is Russia's most important source of natural gas, with more than 90% of Russia's natural gas being produced there. The region also accounts for 12% of Russia's oil production. Both Gazprom (Russia's largest company) and Novatek (Russia's second largest gas producer) have important production fields in this region (http://en.wikipedia.org/wiki/Yamalo-Nenets-Autonomous-Okrug).

3 Dataset and analysis

This section gives an overview of the meteorological dataset used in the analysis in this report. Furthermore, it contains a description of how the various climate parameters were computed.

3.1 Meteorological stations at the Yamalo-Nenets AO

We have analysed data from four weather stations (Figure 2). These stations are located at the west coast (Mare-Sale) of the Yamal peninsula and on the southern areas of Yamal (from west to east: Salekhard, Nadym and Tarko-Sale. Meta data for each station is given in the Tables 1- 2. The observation period for each station varies widely. Salekhard has the longest observation period, with more than 100 years.

An overview of the mean monthly temperature and precipitation for the normal period 1961-1990 for all stations are presented in the Tables 3- 4 and Figure 3. The average summer temperatures are rather similar for the three inland stations Salekhard, Nadym and Tarko-Sale (+14-16°C in July), while the coastal station Mare-Sale is much colder in July with only +7°C. In winter, the inland stations Salekhard, Nadym and Tarko-Sale are slightly colder (-25°C in January) than the coastal station Mare-Sale (-22°C in January). Also for precipitation, the maximum differences between the inland and coast are found during summer. In July, the inland stations show average precipitation sums between 60 and 70 mm, while it is only 30 mm at Mare-Sale in July. At the inland stations, this represents the annual maximum (August for Tarko-Sale), while the annual maximum precipitaion is measured in September at Mare-Sale (40 mm). The minimum precipitation is measured in winter and early spring: February for inland stations (18 mm) and March for Mare-Sale (15 mm). At the coastal station Mare-Sale, the precipitation is only slightly increasing from early spring to a maximum in Septempber.

Sea ice covers the Kara sea for over nine months a year (Figure 4). Maximum sea ice extent is usually observed in March, while the minimum extent usually occur in September. The station Mare-Sale is located by the coast, and the seasonal temperature and precipitation at this station is therefore highly influenced by the duration and extent of the sea ice of the Kara sea. In Figure 5 time-series of the sea-ice extent in August in the Kara sea is shown for the period 1900-2000.

WMO number	Station name	Elevation m a.s.l.	Start	Temperature		Precipitation		Snow depth		Snow
				monthly	daily	monthly	daily	monthly	daily	period
23552	TARKO-SALE	27	1936	1937-2008	1957-2008	1936-2008	1936-2008	1937-2008	1966-2008	1966-2008
23330	SALEKHARD	35	1883	1883-2008	1951-2008	1891-2008	1891-2008	1962-2008	1973-2008	1882-2008
23032	MARE-SALE	24	1914	1914-2008	1966-2008	1928-2008	1928-2008			1914-2008
23445	NADYM	15	1943	1954-2008		1943-2008				

Table 1: *Observation periods of the four meteorological stations at the Yamalo-Nenets AO.*

WMO number	tation name	Station relocation	Rain gauge replacement
23552	TARKO-SALE	-	1953.-.06
23330	SALEKHARD	1973 -	1956.-.02
23032	MARE-SALE	-	1951 29.08
23445	NADYM	-	-

Table 2: *Relocation of the meteorological stations at the Yamal peninsula (Svyashchennikov, 2010).*

WMO number	Station name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
23552	TARKO-SALE	-25.7	-24.3	-16.2	-9.2	-1.3	9.7	16.3	12	5.6	-5.6	-16.2	-22
23330	SALEKHARD	-24.8	-23.9	-16.2	-9.9	-2	7.9	14.3	11	5.1	-4.8	-15.3	-20.9
23032	MARE-SALE	-22.6	-22.6	-18.2	-13.9	-5.9	1.4	7.2	6.7	3.3	-5.1	-13.9	-17.9
23445	NADYM	-24.4	-23.1	-15.1	-8.7	-1	9.1	15.8	11.7	5.7	-5.1	-15.3	-20.6

Table 3: *Mean monthly temperature for the normal period (1961-1990).*

WMO number	Station name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
23552	TARKO-SALE	26.2	18.7	24.9	25.4	35.5	48.9	61.5	65	58.3	47.9	37.9	29.8
23330	SALEKHARD	20.7	18.5	20.4	24.6	34.9	51.9	71.2	64	50.8	40.4	28	26.1
23032	MARE-SALE	20.1	17.3	15.5	16.4	20.1	25.4	30.2	37.9	40.8	28.7	23.4	22.2
23445	NADYM	24.2	17.8	21.5	25.5	38.1	55	68.5	61.9	61.1	45.8	33.4	26.5

Table 4: *Mean monthly precipitation sum for the normal period (1961-1990).*

Figure 2: The four meteorological stations are shown on a satellite image of Yamal (Google Earth).

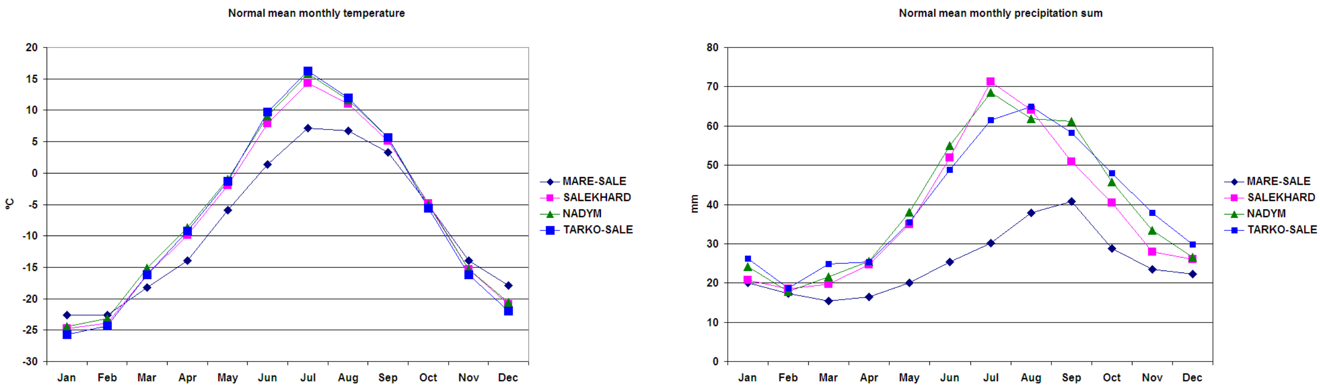


Figure 3: Mean monthly temperature and precipitation for the normal period 1961-1990.

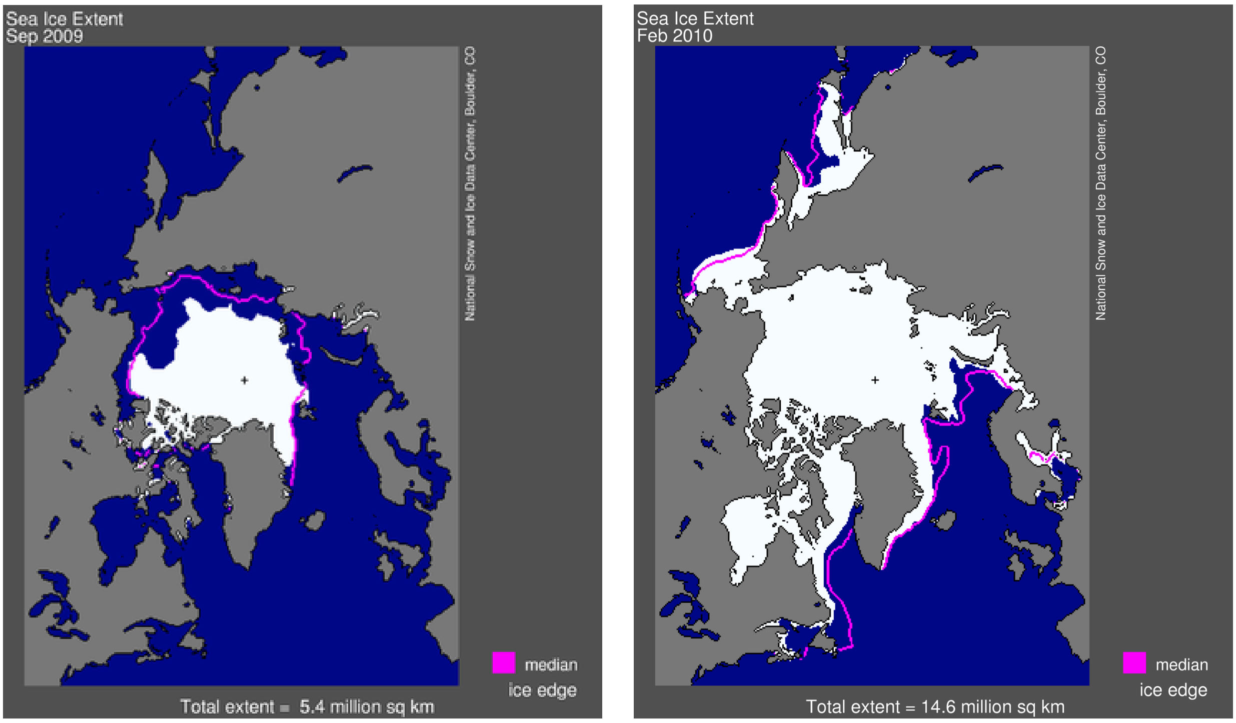


Figure 4: Sea ice extent in the Arctic in February 2010 and September 2009 (Fetterer et al., 2009). The images show the total area of the ocean covered with at least 15% ice. The median line shows the typical ice extent for that month, based on data from 1979 to 2000.

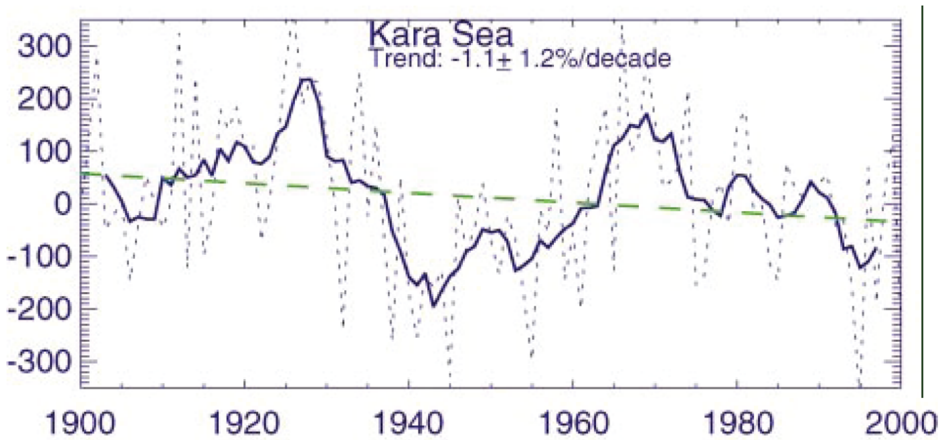


Figure 5: Time series of the August ice-extent anomalies (31000 km^2) in the Kara sea. Dotted lines show yearly August values, solid lines show 6-year running means, green dashed lines show linear trends (Polyakov et al., 2002).

3.2 Time-series analysis

In this Section we describe how the different climate parameters were computed. Decadal scale variability in the dataset are studied by applying a 10 year gauss filter. Results from the analysis are presented in Chapter 4.

3.2.1 Mean temperature

The mean annual temperature is computed from the mean monthly temperatures of a calendar year. Decadal-scale variability is illustrated in the figures by computing the deviation from the mean temperature during the normal period (1961-1990) (example in Figures 3).

Seasonal mean temperature has also been computed according to standard season definitions. Autumn consists of the months September, October and November. Winter consists of the months December, January and February, spring consists of the months March, April and May, while summer consists of the months June, July and August.

For computing annual values a minimum of ten months of data was required within the same year. A stricter criterion was applied to compute seasonal values by requiring observations for all three months.

3.2.2 Annual precipitation sum

The annual precipitation sum is the sum of monthly precipitation during a calendar year. Decadal scale variability is studied by computing the deviation from the mean annual precipitation sum during the normal period (1961-1990) (example in Figure 3).

To examine seasonal variations, this parameter has also been computed for autumn, winter, spring and summer.

For computing annual values a minimum of ten months of data was required within the same year. A stricter criterion was applied to compute seasonal values by requiring observations for all three months.

3.2.3 Maximum snow depth

Maximum snow depth (cm) was computed for every winter season from *daily* snow measurements. A winter season is defined to follow the hydrological year (from 1 September to 31 August).

3.2.4 Snow season duration

We here define the snow season duration as the period during a hydrological year with permanent snow cover. The daily snow depth data from some of the stations have been observed irregularily in periods. Most of the time daily observations have been carried out, but in certain periods snow depth have been measured approx. every 14 days (Figure 6). This makes it difficult to identify the start and end of the snow season directly from the snow depth data. Therefore, we applied a snow period data set provided by Pavel Svyashchennikov, AARI (Arctic and Antarctic Research Institute, St. Petersburg, Russia). This data set consists of dates of start and end of the season with permanent snow cover, as well as number of days in between (snow season duration). The definition used for determining these dates is based on two criterions: 1) at least 50% of the ground around the station should be covered by snow; and 2) snow depth observations at the station. Maximum three snowfree succeding days are allowed within this period of permanent snow cover. Furthermore, the snow season duration was computed as the number of days between the first and the last day. These days constitute the period of the hydrological year with permanent snow cover, and thereby excludes short periods with snow fall followed by melt episodes.

3.2.5 Rain-on-snow events

Rain-on-snow events are typically mild weather events leading to rain falling on an existing snow cover. The consequences of such an event is often extensive snow melt and densification of the snow pack. If the event is followed by a period with very cold weather, strong ice layers can be created in the snow pack. Such ice layers are known to act as a barrier to ungulate grazing, and in severe cases may lead to starvation of reindeers.

In our analysis we define a rain-on-snow event as a day when the precipitation falls as rain (more than 1 mm) on a snow-covered ground (more than 5 cm snow depth). If the air temperature is above 1°C the precipitation is assumed to fall as rain. Rain-on-snow events are only computed for Tarko-Sale and Salekhard, because both Mare-Sale and Nadym are missing daily snow depth observations (Table 1).

3.2.6 Cold periods

We have studied degree days as a measure of how cold it has been and how long it has been cold. We have counted the number of days with temperatures below 0°C, -15°C and -30°C for each hydrological year (1 September-31 August). Additionally, we have computed the cumulated degree days. This is the sum of average daily degrees for days with temperatures below the applied threshold temperature. We computed degree days for hydrological years and not for calendar years. To avoid misinterpretation of trends introduced by missing data, we excluded years with more than 15 days with missing data.

Loose snow structures (depth hoar crystals) are favourable for accessing the food below the snow pack. Depth hoar crystals form preferentially in cold, continental type climate. The higher the temperature gradient between the snow surface and the ground surface is, the more efficient the formation of depth hoar crystals is. This gradient depends on the snow surface temperature, the ground surface temperature and the snow depth. Hence, long periods with cold weather favours the generation of depth hoar crystals, and are therefore favourable for the reindeers access to food through the snow.

3.2.7 Growing season

Growing degree days are a measurement of the growth and development of plants during the growing season. Development does not occur at this time unless the temperature is above a minimum threshold value (base temperature). The base temperature varies for different organisms, but is often set to +5°. Growing degree days is not of importance for reindeer winter pastures, but is included to show some historical climatic aspects of the summer pastures.

We have counted the number of days with temperatures abowe +5°C for each calendar year (1 January-31 December). Additionally, we have computed the cumulated growing degree days. This is the sum of average daily degrees for days with temperatures abowe +5°C.

4 Results and discussion

This Section contains figures of the climate parameters computed for the stations Mare-Sale, Salekhard, Nadym and Tarko-Sale. The climate parameters are:

1. Mean temperature (annual and seasonal values)
2. Precipitation sum (annual and seasonal values)
3. Maximum snow depth (annual values)
4. Snow season duration (including first and last day of snow season)
5. Rain-on-snow events
6. Cold season and degree days
7. Growing season and degree days

4.1 Meteorological stations

4.1.1 Mare-Sale

Results for Mare-Sale meteorological station are shown in Figures 7- 10.

4.1.2 Salekhard

Results for Salekhard meteorological station are shown in Figures 11- 16.

4.1.3 Nadym

Results for Nadym meteorological station are shown in Figure 17.

4.1.4 Tarko-Sale

Results for Tarko-Sale meteorological station are shown in Figures 18- 22.

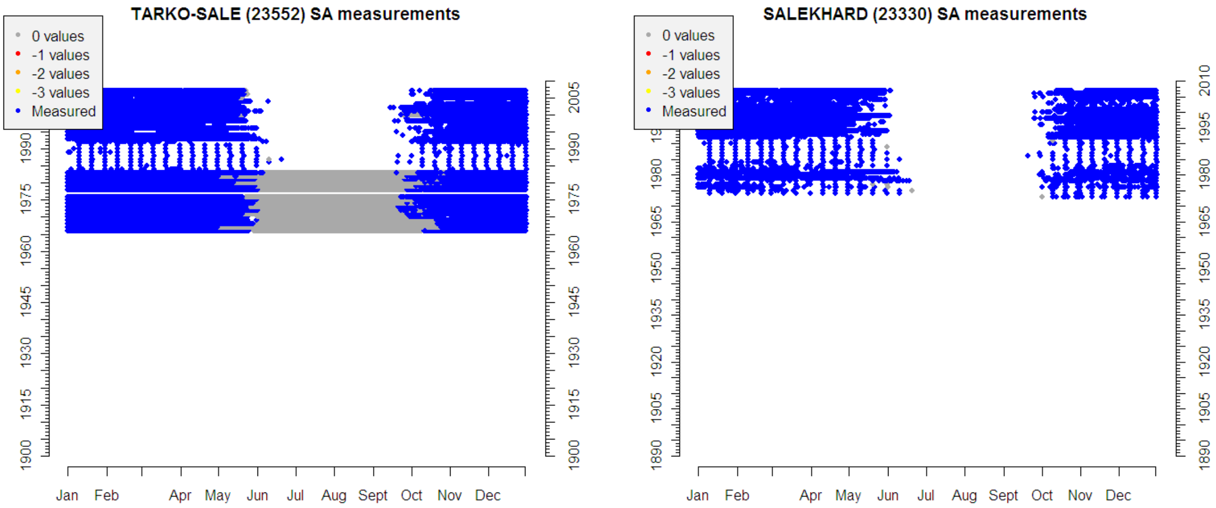


Figure 6: Example of the daily snow depth data which in some periods are observed with certain days interval. Illustration of the difficulties with determining start and end of the snow season.

Figure 7: *Mare-Sale meteorological station: Temperature and precipitation.*

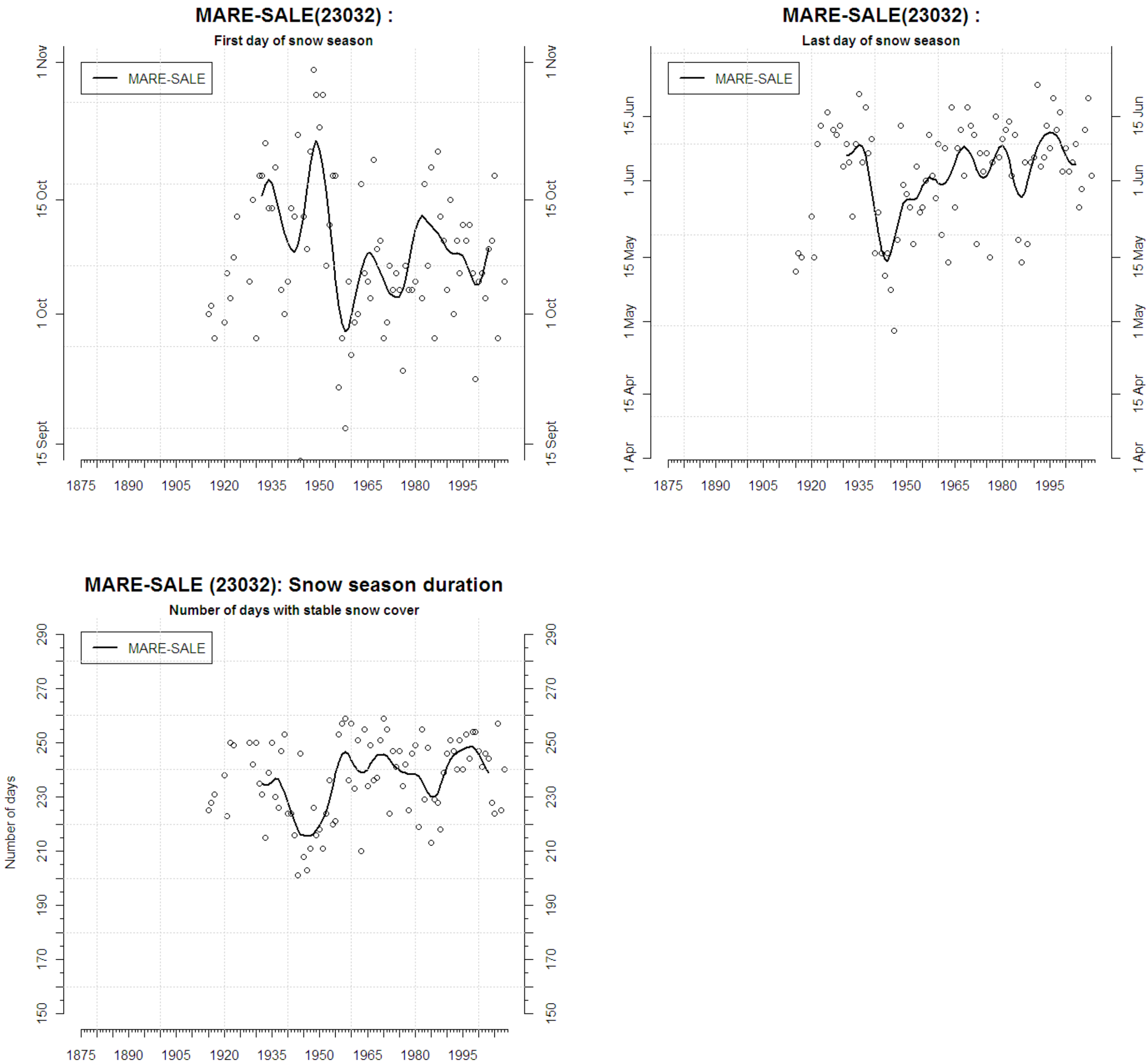


Figure 8: *Mare-Sale meteorological station: Start, end and duration of snow season.*

Figure 9: *Mare-Sale meteorological station: Cold periods.*

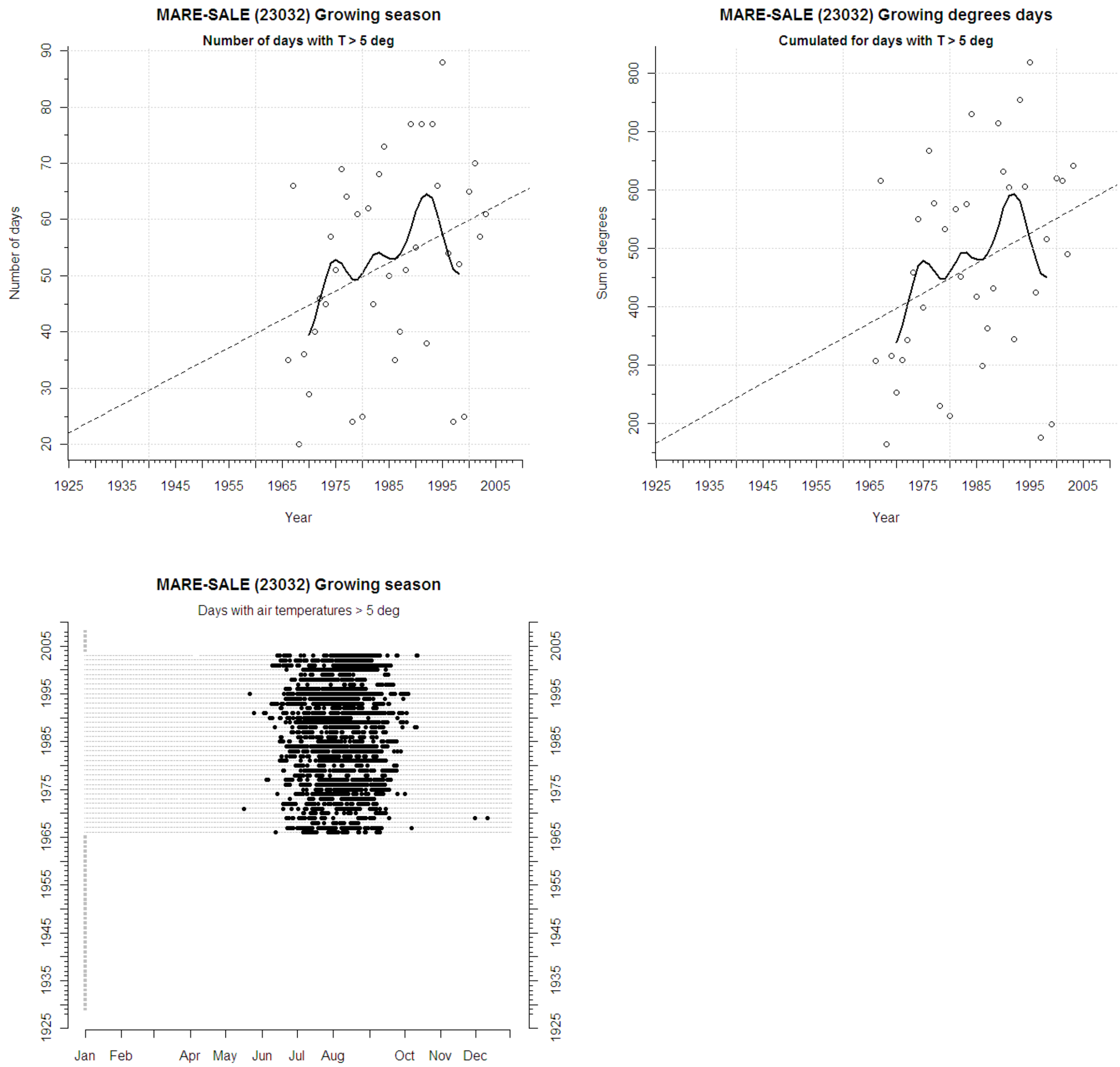


Figure 10: *Mare-Sale meteorological station: Degree days and growing season.*

Figure 11: *Salekhard meteorological station: Temperature and precipitation.*

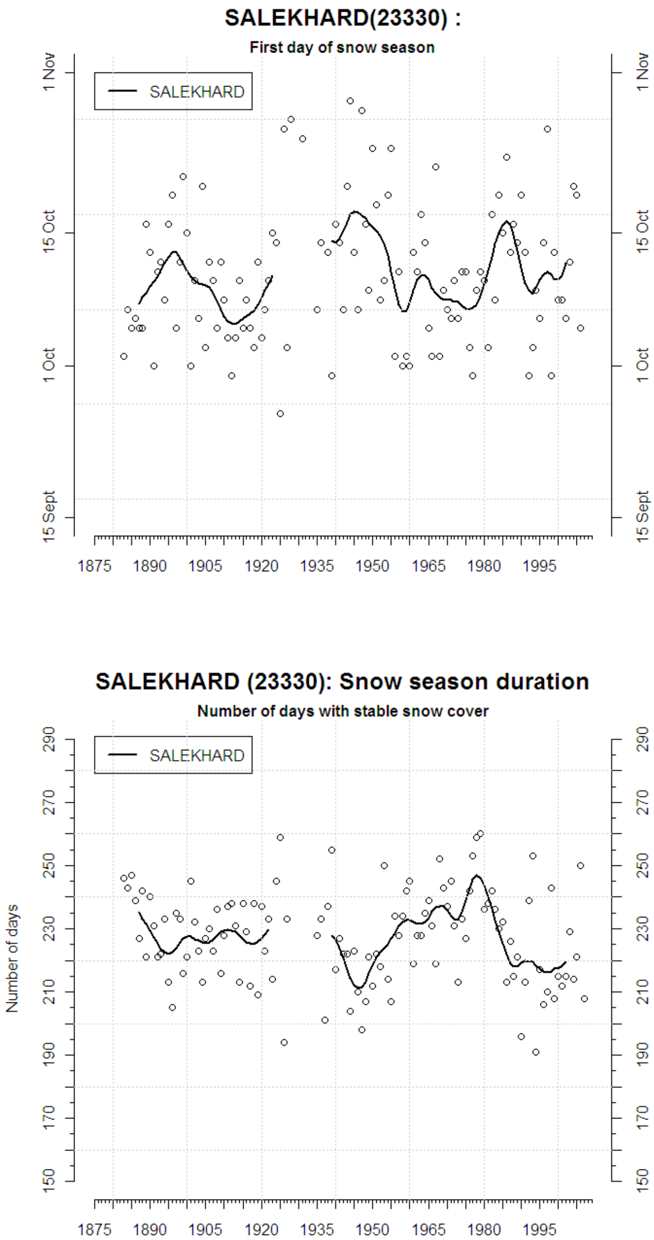


Figure 12: *Salekhard meteorological station: Start, end and duration of snow season.*

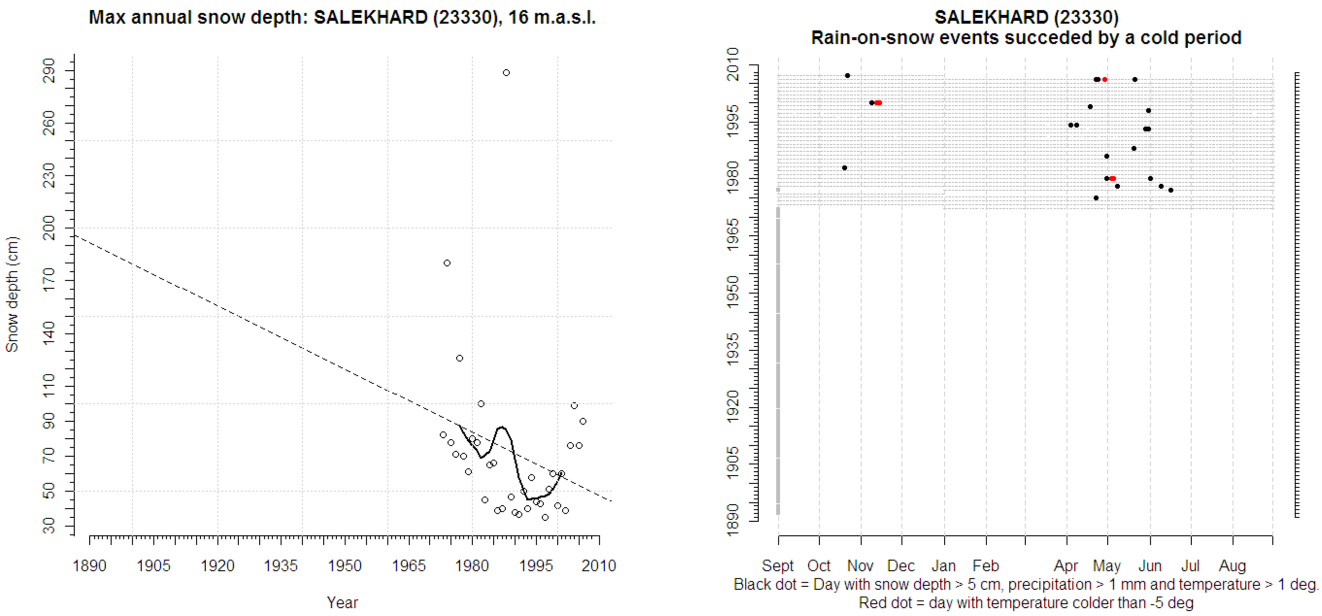


Figure 13: *Salekhard meteorological station: Maximum snow depth and rain-on-snow events.*

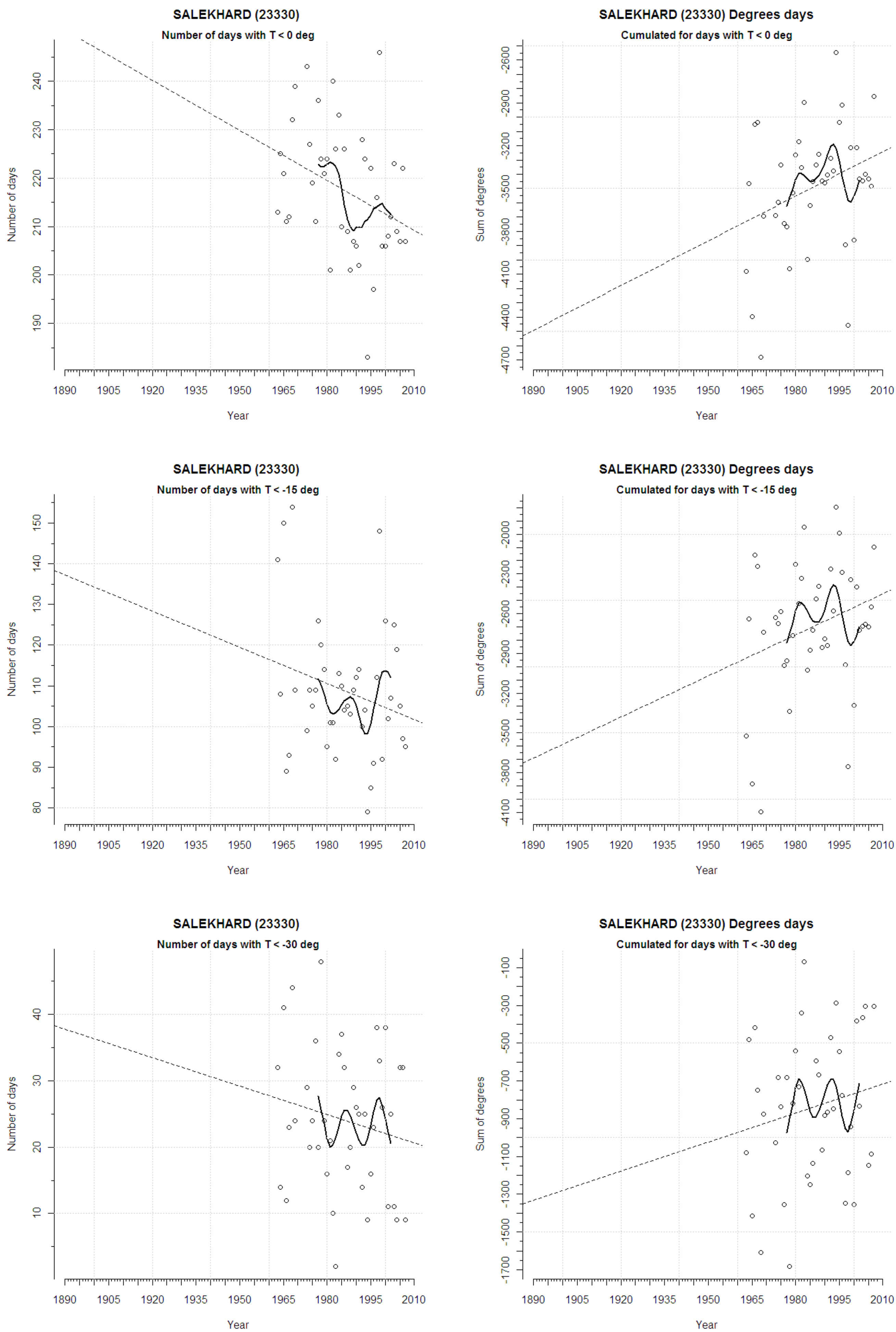


Figure 14: *Salekhard meteorological station: Degree days and cold periods.*

Figure 15: *Salekhard meteorological station: Cold periods.*

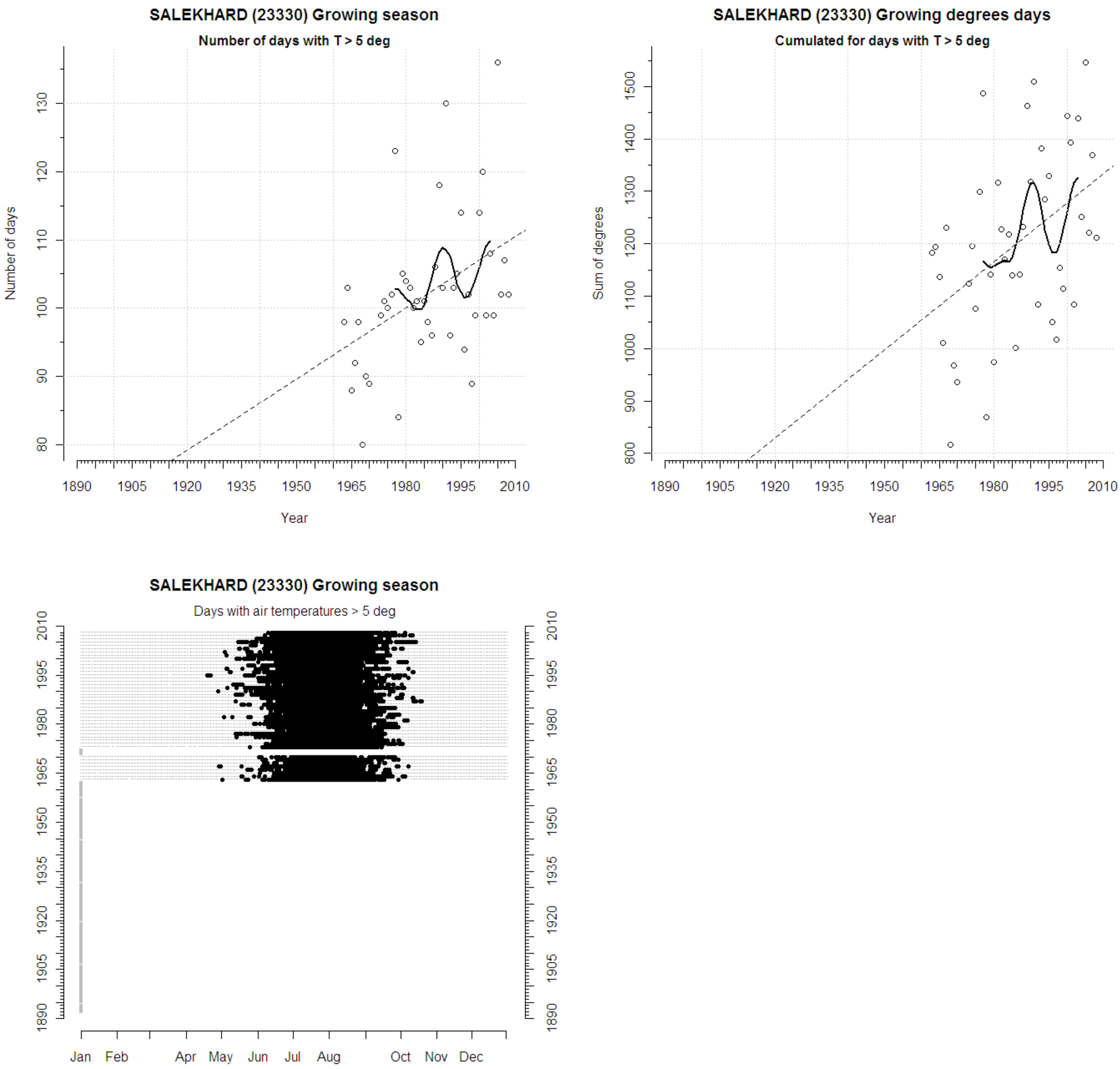


Figure 16: *Salekhard meteorological station: Degree days and growing season.*

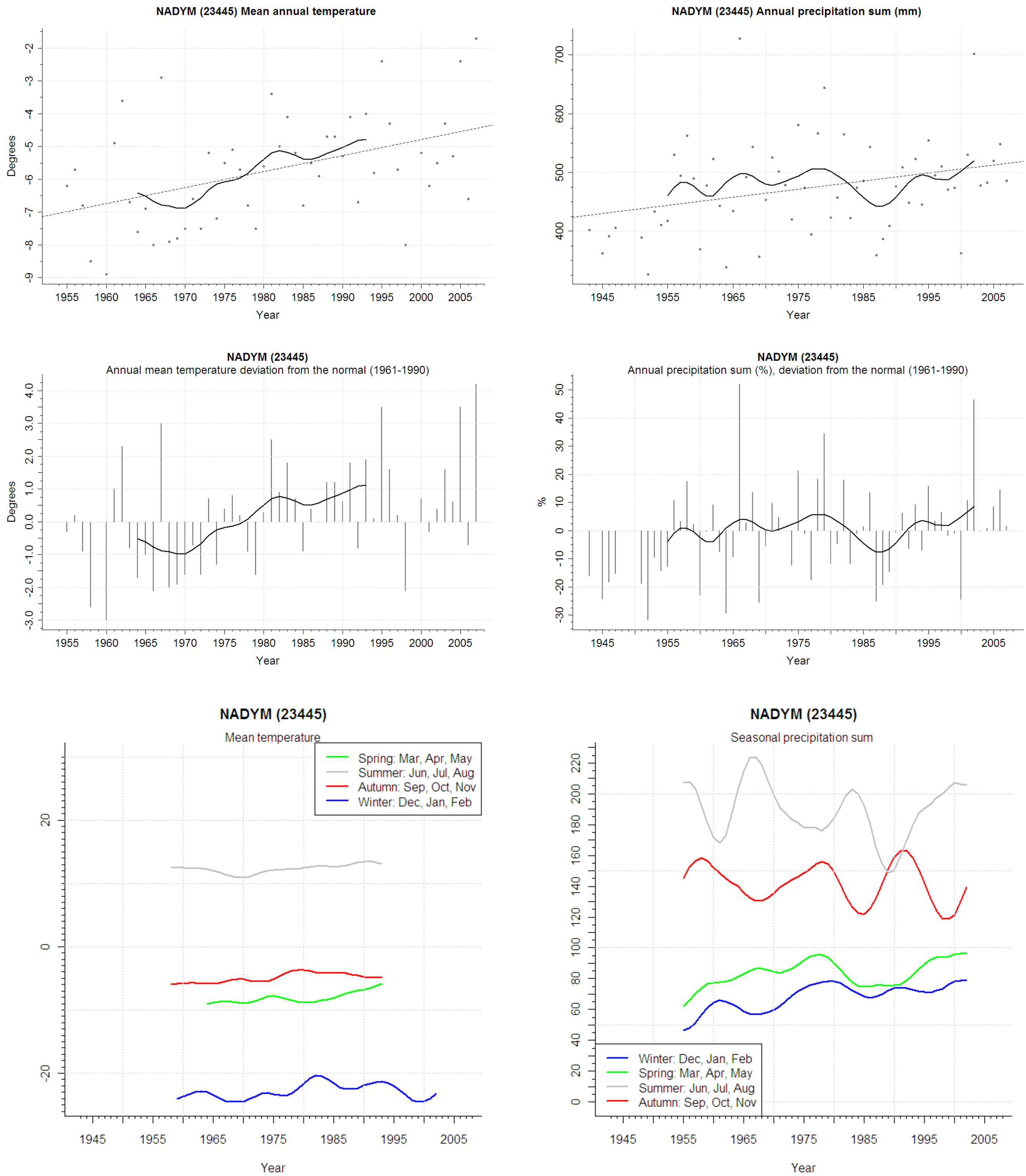


Figure 17: *Nadym meteorological station: Temperature and precipitation.*

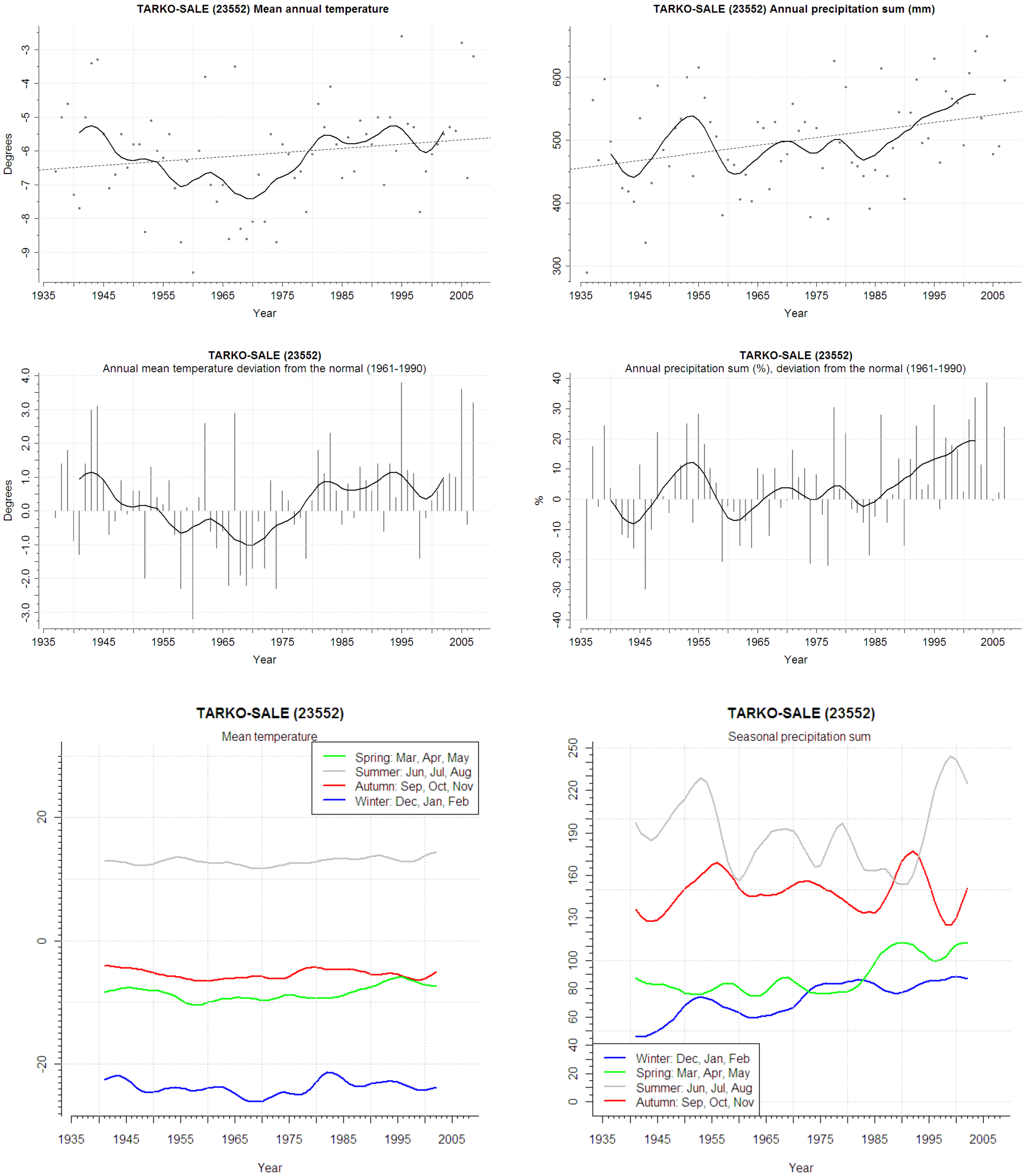


Figure 18: *Tarko-Sale meteorological station: Temperature and precipitation.*

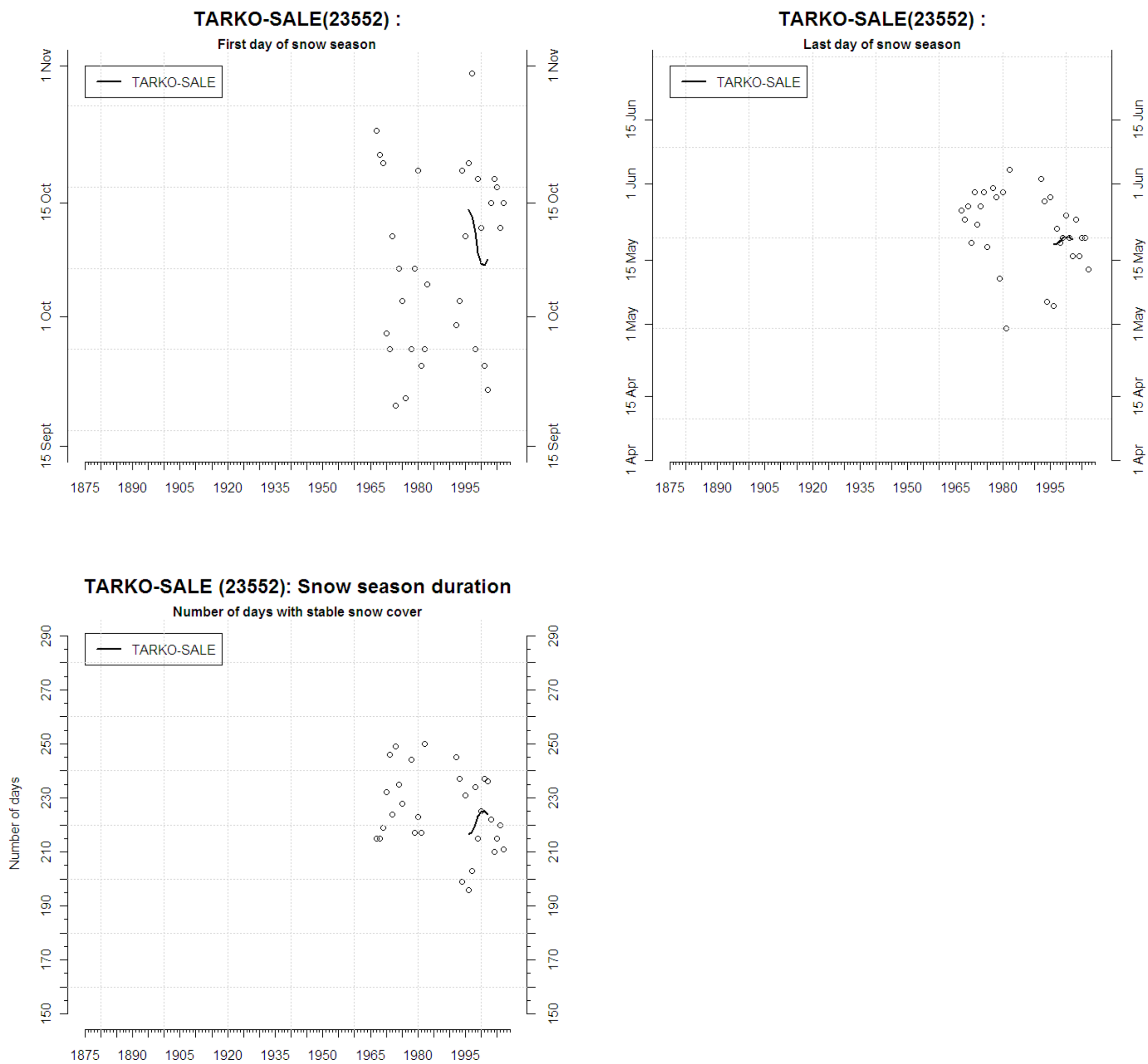


Figure 19: *Tarko-Sale meteorological station: Start, end and duration of snow season.*

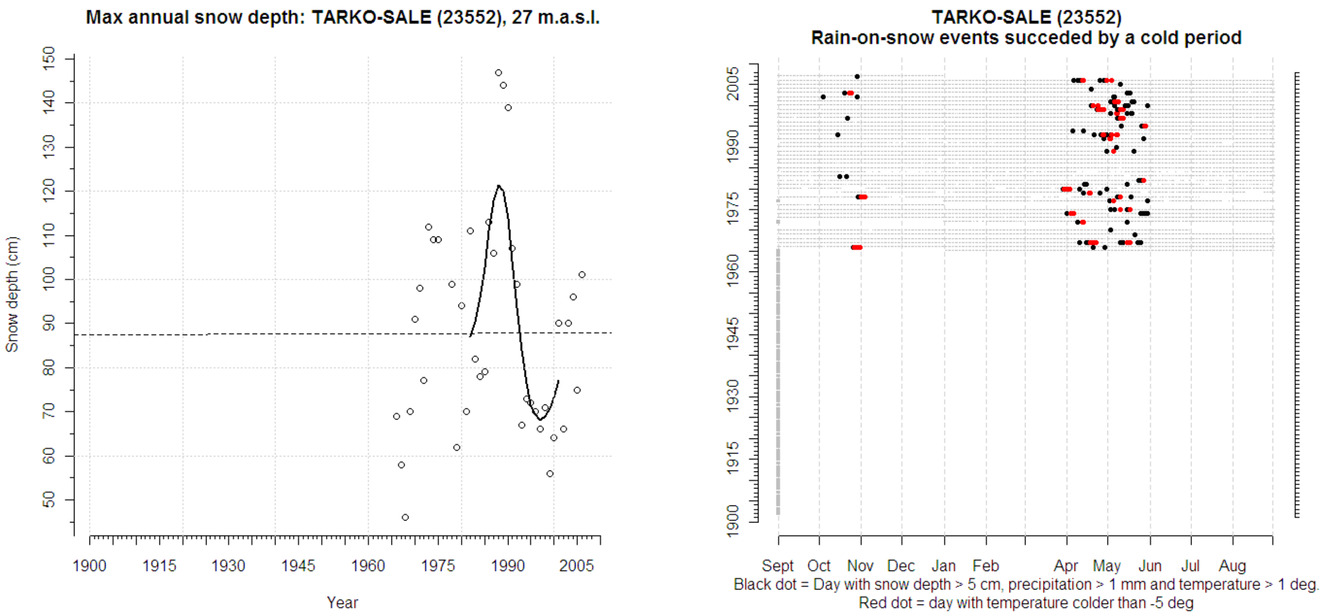


Figure 20: *Tarko-Sale meteorological station: Maximum snow depth and rain-on-snow events.*

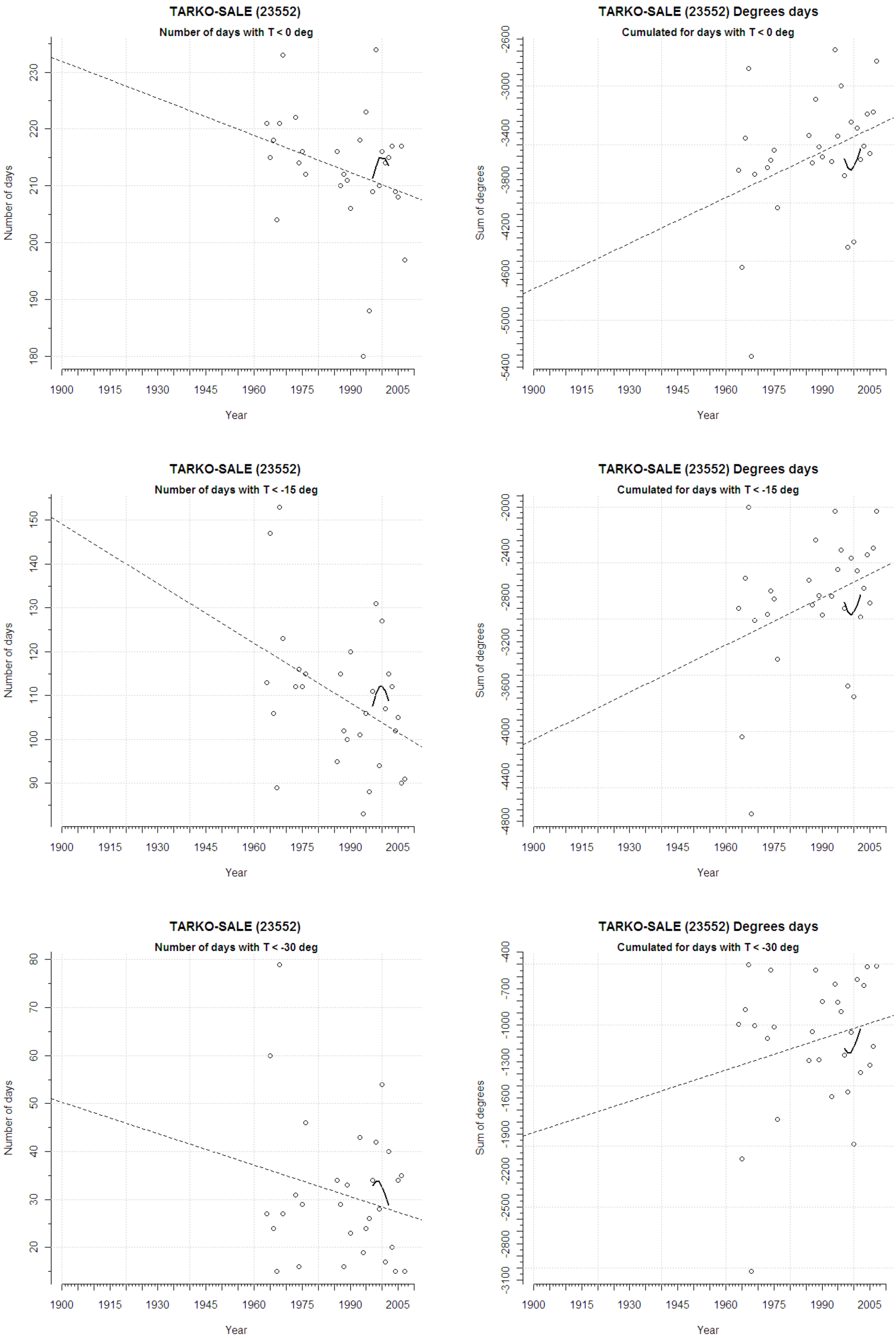


Figure 21: *Tarko-Sale meteorological station: Degree days and cold periods.*

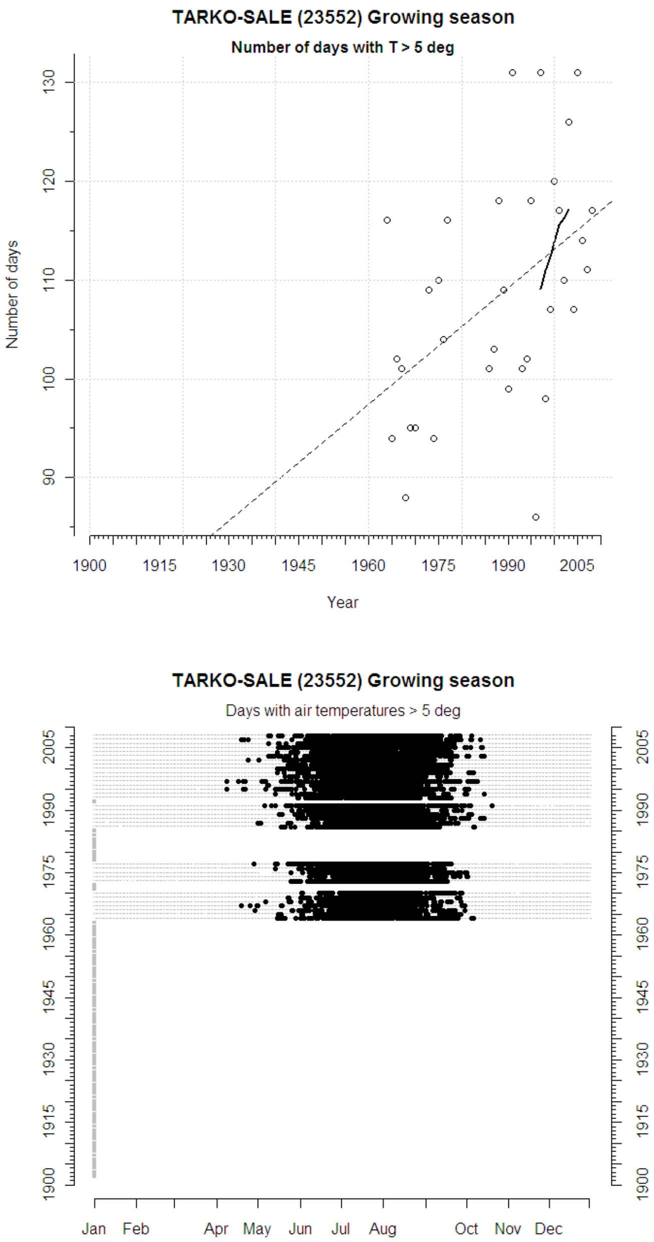


Figure 22: *Tarko-Sale meteorological station: Degree days and growing season.*

4.2 Comparison of the climate of the meteorological stations in the Yamalo-Nenets AO

4.2.1 Annual and seasonal temperature

Long-term linear trends for the period 1900-2008 are listed for Salekhard in Table 5. The other meteorological stations do not have 100 years long temperature series. The linear trend in annual mean temperature for Salekhard is 0.05°C per decade (0.5°C per 100 years, not statistically significant). This is sligtly less than the linear trend of 0.09°C per decade found for the Arctic (60°-90° N) for the period 1900-2003 (ACIA, 2005, p. 36). The long-term linear trends for the seasons are both negative (autumn and winter) and positive (spring and summer). Only the trend for the spring is statistically significant with an increase of 0.18°C per decade (1.8°C per 100 years). Increasing spring temperatures have also been observed several places in Norway and Svalbard (Hanssen-Bauer et al., 2009; Førland et al., 2009).

For all stations, the decadal scale variability is large compared to the long-term trends (Figure 23). The graph of normalized mean annual temperature (deviation from normal period 1961-1990) show that the decadal scale variability for the four stations is very similar. It mainly follows the periods described for the Arctic (60°-90° N) (ACIA, 2005, p. 35).:

1. Increasing temperatures from 1900 to the mid-1940s (often referred to as the "early 20th century warming").

2. Decreasing temperatures from the mid-1940s until about the mid-1960s.

3. A "recent warming" from the 1960s to 2003. For Yamal this is shiftet to the period 1965/70s-1990/95s.

These periods are also described for Norway (Førland et al., 2000; Hanssen-Bauer, 2005; Hanssen-Bauer et al., 2009; Førland et al., 2009), but in Norway the "early 20th century warming" culminated in the 1930s, a decade earlier. Possible causes for the "early 20th century warming" and the following cooling have been discussed in litterature. Wood and Overland (2009) sums up the evidences and conclude that random variability in atmospheric circulation and its implications for ocean circulation probably explains the observed anomalies.

Recent changes in temperature from the standard normalperiod 1961-1990 to the period 1979-2008 are shown in the Tables 6- 7. A maximum of 5 years of missing data within each 30 year period was allowed. Both annual and seasonal temperatures have increased, but particularily spring temperatures show the largest increase for three stations (Salekhard, Nadym and Tarko-Sale). Note, however that Mare-Sale, which for most seasons show smaller temperature increase than the other stations, show largest warming in the fall. This may be caused by the general trends toward less sea ice extent in summer/autumn.

Mare-Sale, which is located by the Kara Sea, has the lowest mean annual temperature. The other three stations (Tarko-Sale, Nadym and Salekhard) are closer in temperatures. The seasonal temperature variability is different at Mare-Sale as compared to the three other stations, particularily during spring and summer which are still very cold months at Mare-Sale. The presence of sea ice during spring and summer (Figure 30) greatly influences the seasonal temperature. Autumn and winter temperatures are similar at all four stations.

Figure 23: *Annual and seasonal temperature: Comparison of all stations at Yamal. 10 year Gauss filter.*

Station number	Station Name	Linear trend (°C per decade) Annual	Autumn	Winter	Spring	Summer
23552	Tarko-sale	-	-	-	-	-
23330	Salekhard	0.05	-0.01	-0.04	**0.18**	0.06
23032	Mare-sale	-	-	-	-	-
23445	Nadym	-	-	-	-	-

Table 5: *Least squares linear trends in annual and seasonal temperature series (°C per decade) during the period 1900-2008. Trends significant at the 1% level according to the Mann-Kendall test are shown in* **bold** *type. Temperature series starting later than 1900 are excluded from the analysis.*

		1961-90	1979-08	Change
23552	Tarko-sale	-6.4	-5.5	0.9
23330	Salekhard	-6.6	-5.7	0.9
23032	Mare-sale	-8.5	-7.8	0.7
23445	Nadym	-5.9	-5.1	0.8

Table 6: *Mean annual temperature (°C) for the periods 1961-1990 and 1979-2008, and change in temperature (°C) from 1961-1990 to 1979-2008.*

Station	Station	Autumn			Winter		
number	name	1961-90	1979-08	Change	1961-90	1979-08	Change
23552	Tarko-sale	-5.4	-4.9	0.5	-24.0	-23.1	0.9
23330	Salekhard	-5.0	-4.2	0.8	-23.2	-22.4	0.8
23032	Mare-sale	-5.2	-4.3	0.9	-20.9	-20.7	0.2
23445	Nadym	-4.9	-4.3	0.6	-22.7	-22.2	0.5

Table 7: *Mean autumn and winter temperature (°C) for the periods 1961-1990 and 1979-2008, and change in temperature (°C) from 1961-1990 to 1979-2008.*

Station	Station	Spring			Summer		
number	name	1961-90	1979-08	Change	1961-90	1979-08	Change
23552	Tarko-sale	-8.9	-7.7	1.2	12.7	13.5	0.8
23330	Salekhard	-9.4	-8.1	1.3	11.1	11.8	0.7
23032	Mare-sale	-12.7	-12.1	0.6	5.1	5.7	0.6
23445	Nadym	-8.2	-7.0	1.2	12.2	13.0	0.8

Table 8: *Mean spring and summer temperature (°C) for the periods 1961-1990 and 1979-2008, and change in temperature (°C) from 1961-1990 to 1979-2008.*

4.2.2 Annual and seasonal precipitation

Long-term linear trends for the period 1900-2008 are listed for Salekhard in Table 9. The other meteorological stations do not have 100 years long precipitation series. The linear trend in annual precipitation sum for Salekhard is 3.3% per decade (33% per 100 years, statistically significant at 1% level). This trend is larger than the linear trend of 1.4% per decade (14% per 100 years) found for the Arctic (60°-90° N) for the period 1900-2003 (ACIA, 2005, p.42). The long-term linear trends are positive and significant for all seasons in Salekhard (Table 9). Winter and spring have the largest positive trends with 5.3% and 4.5% increase per decade, respectively.

Recent changes in precipitation are analyzed by comparing the precipitation sum during the two periods 1961-1990 and 1979-2008 (Tables 10- 12). All stations show an increase of 2% (Nadym) to 9% (Tarko-Sale) in annual precipitation sum from the period 1961-1990 to the period 1979-2008. For the seasons the stations show some increasing precipitation for all seasons with three insignificant exceptions: winter and spring precipitation for Mare-Sale decreases (-3% and -5%) as well as the autumn precipitation for Salekhard (-1%). Largest increase (19%) is observed at Tarko-Sale during the spring.

The differences in decadal variability between the individual stations are larger than for temperature in this region (Figure 24). This is expected since precipitation often varies more locally than temperature. The coastal station Mare-Sale, located by the Kara Sea, receives less precipitation than the other three stations during spring and summer. This might be related to a higher frequency of convective precipitation in the inland areas than at the coast (differences in friction and turbulence over land areas, sea and sea ice).

It should be underlined that there are uncertainties connected to precipitation measurements over time. Methods for correcting measured precipitation depend upon observing practices, which differ between countries (ACIA, 2005, p.39). The history of instrumentally observed precipitation in the former USSR is described in Groisman et al. (1991). Relocation of a station introduces inhomogenities to the precipitation serie. The Salekhard station has been relocated in 1973, and the rain gauge have been replaced in 1956 (Table 2). In Mare-Sale the rain gauge was replaced in 1951, thus the rather abrupt increase in measured precipitation around that time may partly be caused by a following inhomogeneity. Uncertainties are also connected to measurement errors because of undercatch or drifting/blowing snow (Førland and Hanssen-Bauer, 2000; Førland et al., 2006)

Station number	**Station Name**	**Linear trend (% per decade)**				
		Annual	**Autumn**	**Winter**	**Spring**	**Summer**
23552	Tarko-sale	-	-	-	-	-
23330	Salekhard	**3.3**	**2.9**	**5.3**	**4.5**	2.7*
23032	Mare-sale	-	-	-	-	-
23445	Nadym	-	-	-	-	-

Table 9: *Least squares linear trends in annual and seasonal precipitation series (% per decade) during the period 1900-2008. Trends significant at the 1% level according to the Mann-Kendall test are shown in* **bold** *type, while trends significant at the 5% level are marked with a "*". Precipitation series starting later than 1900 are excluded from the analysis.*

		1961-90	**1979-08**	**Change**
23552	Tarko-sale	480.1	525.1	9.4
23330	Salekhard	450.8	470.1	4.3
23032	Mare-sale	297.7	310.0	4.1
23445	Nadym	479.3	489.2	2.1

Table 10: *Annual precipitation sum (mm) for the periods 1961-1990 and 1979-2008, and change (%) in precipitation from 1961-1990 to 1979-2008.*

Figure 24: *Annual and seasonal precipitation sum (mm): Comparison of all stations at Yamal. 10 year Gauss filter.*

Station	**Station**	**Autumn**			**Winter**		
number	**name**	**1961-90**	**1979-08**	**Change**	**1961-90**	**1979-08**	**Change**
23552	Tarko-sale	144.1	148.5	3.1	74.3	83.4	12.2
23330	Salekhard	119.2	117.7	-1.3	64.8	69.9	7.9
23032	Mare-sale	92.8	97.0	4.5	58.9	57.4	-2.5
23445	Nadym	140.3	141.9	1.1	67.9	73.5	8.2

Table 11: *Autumn and winter precipitation sum (mm) for the periods 1961-1990 and 1979-2008, and change (%) in precipitation from 1961-1990 to 1979-2008.*

Station	**Station**	**Spring**			**Summer**		
number	**name**	**1961-90**	**1979-08**	**Change**	**1961-90**	**1979-08**	**Change**
23552	Tarko-sale	85.8	102.0	18.9	175.5	191.1	8.9
23330	Salekhard	79.2	87.5	10.5	187.1	194.3	3.8
23032	Mare-sale	51.9	49.2	-5.2	93.5	105.4	12.7
23445	Nadym	85.1	85.5	0.5	185.4	188.3	1.6

Table 12: *Spring and summer precipitation sum (mm) for the periods 1961-1990 and 1979-2008, change (%) in precipitation from 1961-1990 to 1979-2008.*

4.2.3 Snow season and snow depth

The daily snow depth data series are short and recent, only about 40 years long (see Table 1 and description in Section 3.2.3). Most of the time daily observations have been carried out, but in certain periods snow depth have been measured approx. every 14 days (Figure 6). For these periods maximum annual snow depth have not been computed. Results of maximum annual snow depth for Salekhard and Tarko-Sale are shown in Figure 25 (bottom right). A maximum period appeared around 1987-1990, followed by a minimum period around 1995.

Snow season duration data series are much longer (Section 3.2.4), of which Salekhard has more than 100 years of data (from 1882) and Mare Sale has nearly 100 years of data (from 1914). Results of first day and last day of the snow season as well as the snow season duration for Mare-Sale and Salekhard are shown in Figure 25. Generally the decadal-scale trends for the two stations are similar until around 1985.

A minimum period for the snow season duration appeared around 1945. This was a warm period corresponding to the "early 20th century warming" (see Section 4.2.1). The snow season started late and ended early. The snow season duration was actually the shortest during the last 100 years for Mare-Sale, but not for Salekhard which has occationally experienced just as short snow season duration in the last 15 years.

Recent changes (from the period 1961-1990 to 1979-2008) in snow season duration is shown in the Tables 13- 14. At Salekhard the snow season duration has decreased with a little more than a week, while at Mare-Sale the duration has increased with a few days. At Figure 25 the period starting around 1985 until today reveal opposite changes in snow season duration at the coastal station Mare-Sale and the inland station Salekhard. This is also the case for the last day of the snow season, but not the first day of the snow season. During spring, the snow season increases in Mare-Sale, while it decreases in Salekhard. These differences are very interesting because the decadal differences were similar at the two stations before 1985, but very different after 1985. This may partly be caused by differences in seasonal precipitation pattern at Mare-Sale and Salekhard (Figure 26). It may also be affected by the fact that Mare-Sale is colder than Salekhard in the spring (Table 3 and Figure 3). In May, the 1961-90 averages at Mare-Sale is -6°C, while it is -2°C at Salekhard. The spring temperature increase after 1961-90 has also been higher at Salekhard and the snow disappears earlier.

		1961-90	**1979-08**	**Change**
23552	Tarko-sale	-	-	-
23330	Salekhard	233	224	-9
23032	Mare-sale	238	240	2
23445	Nadym	-	-	-

Table 13: *Snow season duration: Number of days with permanent snow cover for the periods 1961-1990 and 1979-2008, and change in number of days.*

		1961-90	**1979-08**	**Change**
23552	Tarko-sale	-	-	-
23330	Salekhard	11.10	13.10	2 days later start
23032	Mare-sale	08.10	10.10	2 days later start
23445	Nadym	-	-	-

Table 14: *Snow season duration: First day with permanent snow cover for the periods 1961-1990 and 1979-2008, and change in number of days.*

		1961-90	1979-08	Change
23552	Tarko-sale	-	-	-
23330	Salekhard	31.05	23.05	8 days earlier end
23032	Mare-sale	04.06	07.06	3 days later end
23445	Nadym	-	-	-

Table 15: *Snow season duration: Last day with permanent snow cover for the periods 1961-1990 and 1979-2008, and change in number of days from 1961-1990 to 1979-2008.*

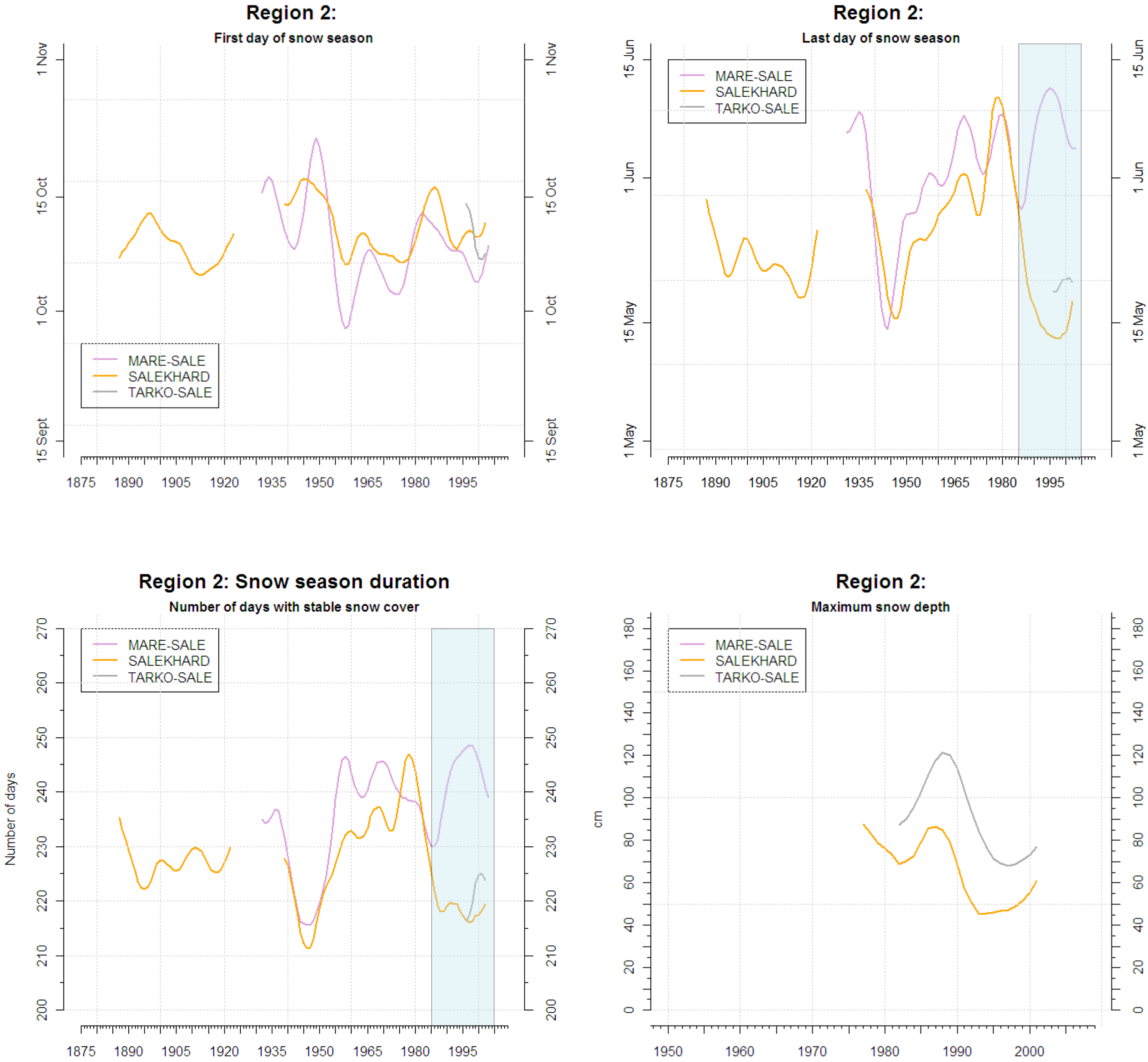


Figure 25: *Start, end and duration of the snow season, as well as maximum annual snow depth: Comparison of all stations at Yamal. Note differences during the period 1985-2005. 10 year Gauss filter.*

Figure 26: *Seasonal precipitation sum and temperature for Mare-Sale and Salekhard. Note differences in precipitation during the period 1985-2005. 10 year Gauss filter.*

4.2.4 Degree days and cold periods

Degree days and cold periods for days with temperatures below 0°C, -15°C and -30°C are shown in Figure 27. The coastal station Mare-Sale has a considerably larger number of days with daily mean temperatures below 0°C than the continental station Salekhard. However, the really cold days (daily temperatures below -30°C) are larger in number in Salekhard than in Mare-Sale. This may be explained by the close location of Mare-Sale to the sea. The presence of sea ice during nine months (including spring and parts of summer) might influence the climate such that the spring and summer temperatures are low. Only in summer the temperature is slightly above 0°C.

Long periods with cold weather favours the generation of depth hoar crystals in the snow pack (loose snow structure), and is therefore favourable for the reindeers access to food through the snow. Changes in the length of these cold periods affect the snow pack and thereby the reindeers food access. To better understand these processes, more studies are needed on changes in snow pack properties with air temperatures and effects on the reindeers food access. The decadal scale variability in Figure 27 shows that a culmination period occurred around 1990-95 with the shortest cold periods since 1960s/1970s.

Changes from the period 1961-90 to 1979-08 in degree days for 0°C, -15°C and -30°C are shown in Tables 16 and 17.

Degree days and cold periods are computed from the daily temperature measurements. As the daily measurement series are available in digital format only since the 1950s/60s, no 100 year trends have been computed (see Table 1). Years with more than 15 days of missing data were excluded in order to avoid misinterpretation of trends. This occurred frequently in the first 10 years of the Salekhard and Mare-Sale daily temperature series.

		1961-90	**1979-08**	**Change**
23552	Tarko-sale	-	-	-
23330	Salekhard	220.7	214.6	-6.1
23032	Mare-sale	246.1	-	-
23445	Nadym	-	-	-

Table 16: *Number of days with temperatures below 0°C for the periods 1961-1990 and 1979-2008, and change in number of days from 1961-1990 to 1979-2008.*

Station number	**Station name**	**-15°C**			**-30°C**		
		1961-90	**1979-08**	**Change**	**1961-90**	**1979-08**	**change**
23552	Tarko-sale	-	-	-	-	-	-
23330	Salekhard	110.8	105.5	-5.3	25.4	22.2	-3.2
23032	Mare-sale	111.3	-	-	21.1	-	-
23445	Nadym	-	-	-	-	-	-

Table 17: *Number of days with temperatures below -15°C and -30°C for the periods 1961-1990 and 1979-2008, and change in number of days from 1961-1990 to 1979-2008.*

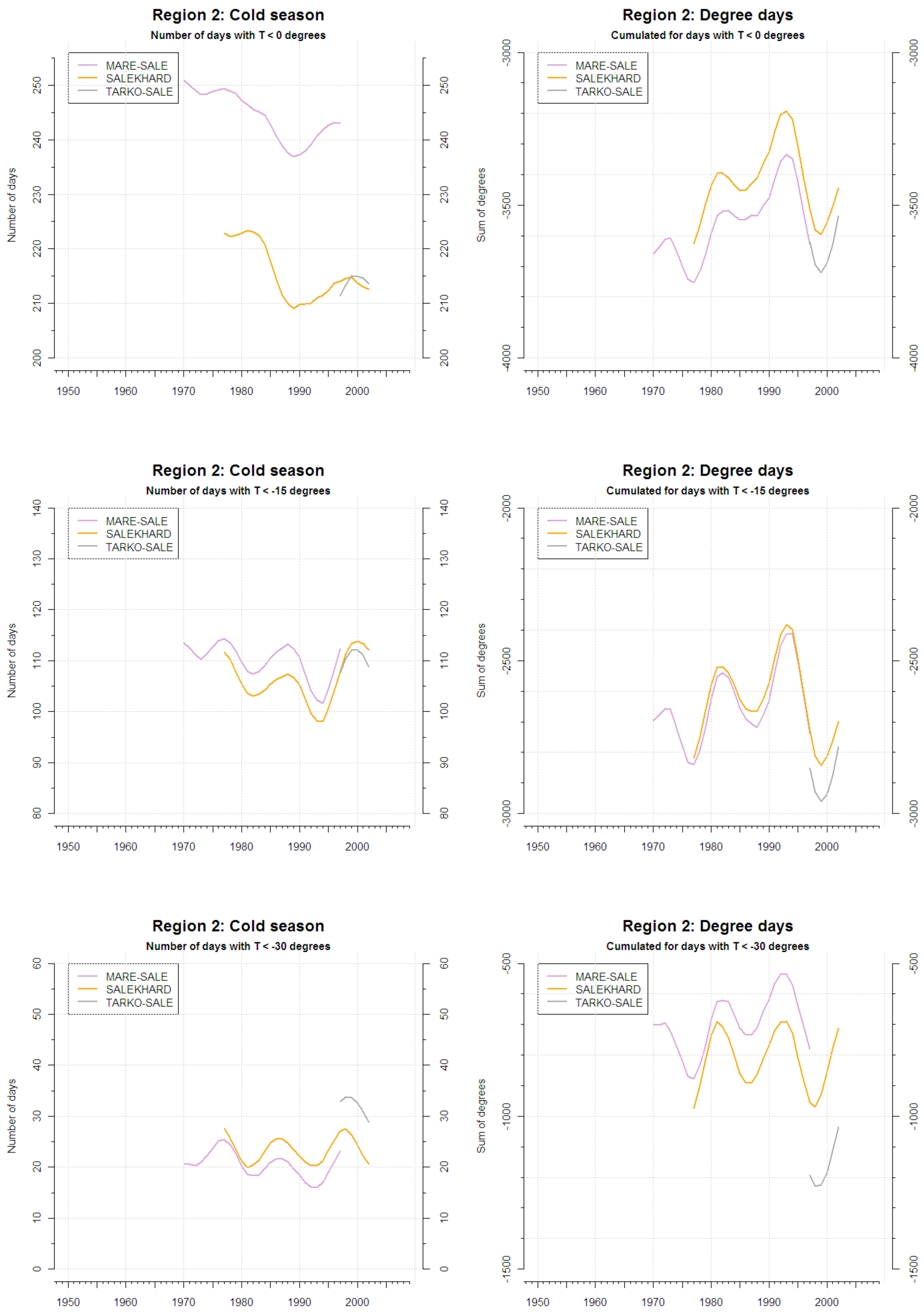


Figure 27: *Cold season and degree days: Comparison of all stations at Yamal. 10 year Gauss filter.*

4.2.5 Degree days and growing season

Since 1960s/1970s the growing season is gradually prolonged for the stations at the Yamalo-Nenets AO (see the Salekhard and Mare-Sale series in Figure 28). Recent changes from the period 1961-90 to 1979-08 in growing degree days are shown in Table 18. For both Salekhard and Mare-Sale the growing season has increased with 6-7 days between the two periods. Note that the duration of the growing seasons at Salekhard is twice as long as the growing season at Mare-Sale and the number of growing degree days is 2-3 times as large. A prolongued growing season increases the plant production during summer, and therefore is positive for the summer pastures of the reindeer.

		1961-90	1979-08	Change
23552	Tarko-sale	-	-	-
23330	Salekhard	99.1	105.0	5.9
23032	Mare-sale	49.0	55.8	6.8
23445	Nadym	-	-	-

Table 18: *Growing season: Number of days with temperatures abowe $5^\circ C$ for the periods 1961-1990 and 1979-2008, and change in number of days from 1961-1990 to 1979-2008.*

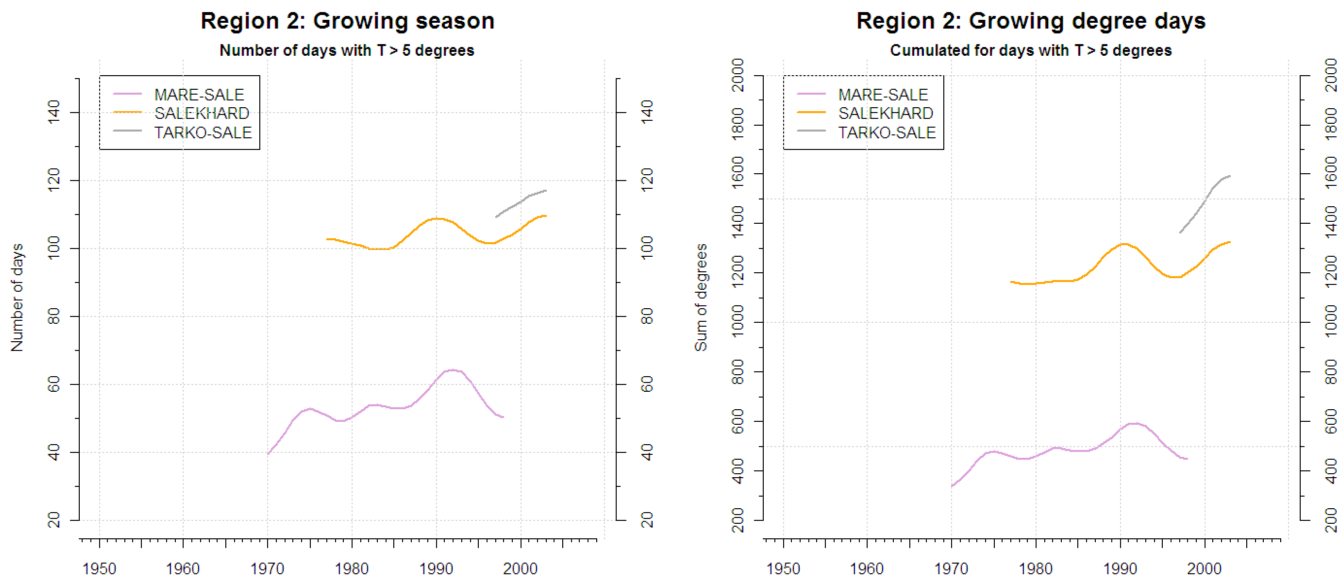


Figure 28: *Growing season and growing degree days: Comparison of all stations at Yamal. 10 year Gauss filter.*

4.3 Sea-ice extent and climate at Mare-Sale

The climate at the coastal station Mare-Sale is in general influenced by the presence of sea-ice, open sea and atmospheric circulation. To study possible influence of sea-ice on seasonal precipitation and temperature we have used time-series of August sea-ice anomaly data from the Kara Sea (Polyakov et al., 2002). August sea-ice represents the situation with minimum annual sea-ice extent in the Kara Sea. However, the sea ice data does not contain any information about the sea ice distribution at the coast around the Mare-Sale station. In the Figures 29- 32 we have plotted the sea-ice data together with precipitation and temperature from Mare-Sale. Correlation coefficients are given in Table 19 and scatterplots are shown in Figures 33- 34.

Generally, the correlations are weak and the temperature data are better correlated with the sea-ice data than the precipitation data. The temperature decreases with increasing sea-ice extent (except during autumn).

For precipitation, there is no correlation with sea ice extent. This relation is probably indirect and complex. More sophisticated analysis is needed to better understand how these factors (sea-ice extent in the vicinity of the station, atmospheric circulation, temperature, precipitation) influence each other.

	Correlation coefficient	
Period	**Precipitation**	**Temperature**
Annual	-0.05	-0.34
Autumn	-0.07	-0.04
Winter	0.16	-0.31
Spring	-0.02	-0.42
Summer	-0.11	-0.39

Table 19: *Correlation coefficients of sea-ice extent, precipitation sum and temperature (seasonal and annual values) for the data plottet in the Figures 29- 32.*

Figure 29: *Sea-ice extent and seasonal temperature (autumn and winter) at the station Mare-Sale. 5 year Gauss filter.*

Figure 30: *Sea-ice extent and seasonal temperature (spring and summer) at the station Mare-Sale. 5 year Gauss filter.*

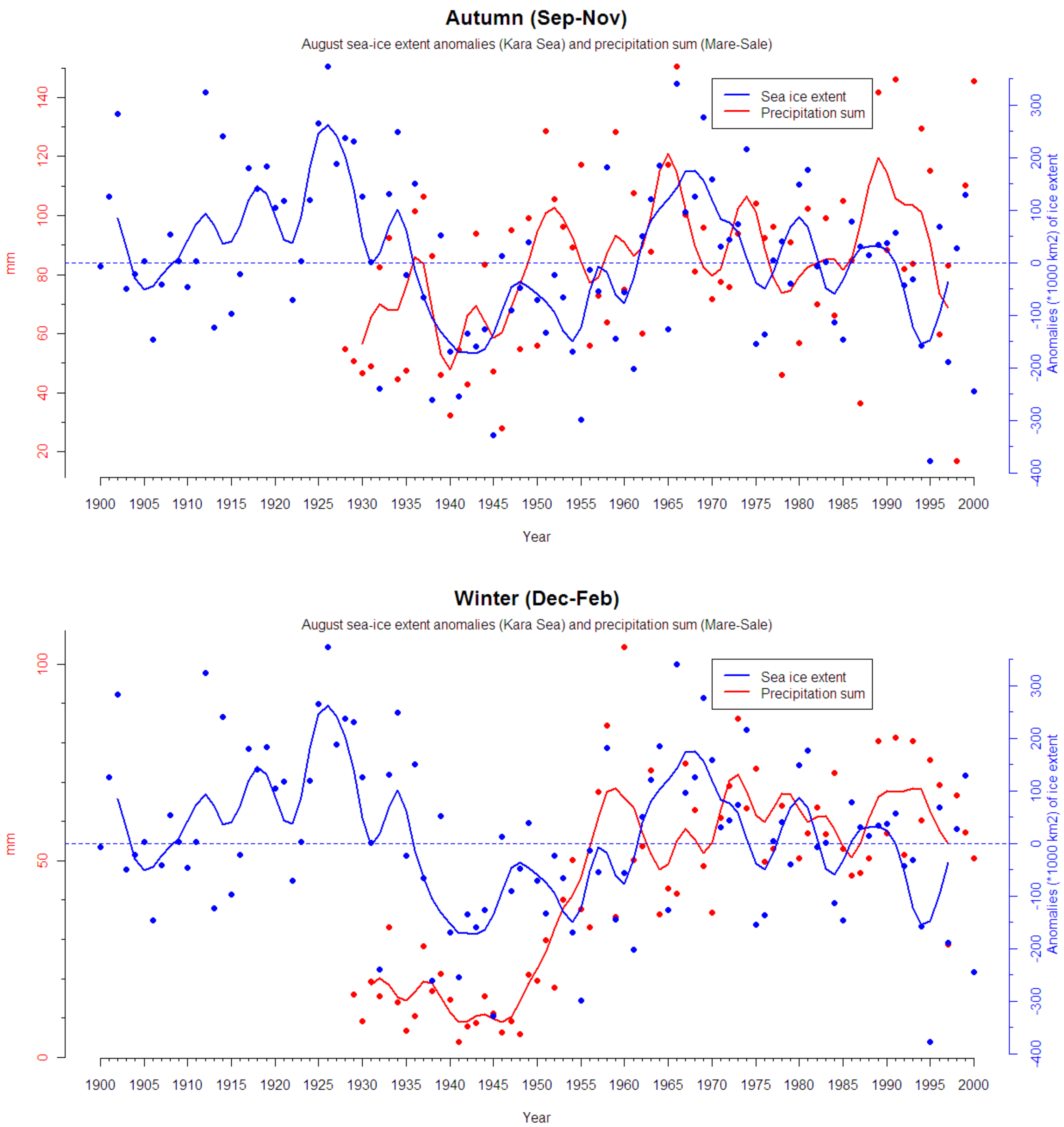
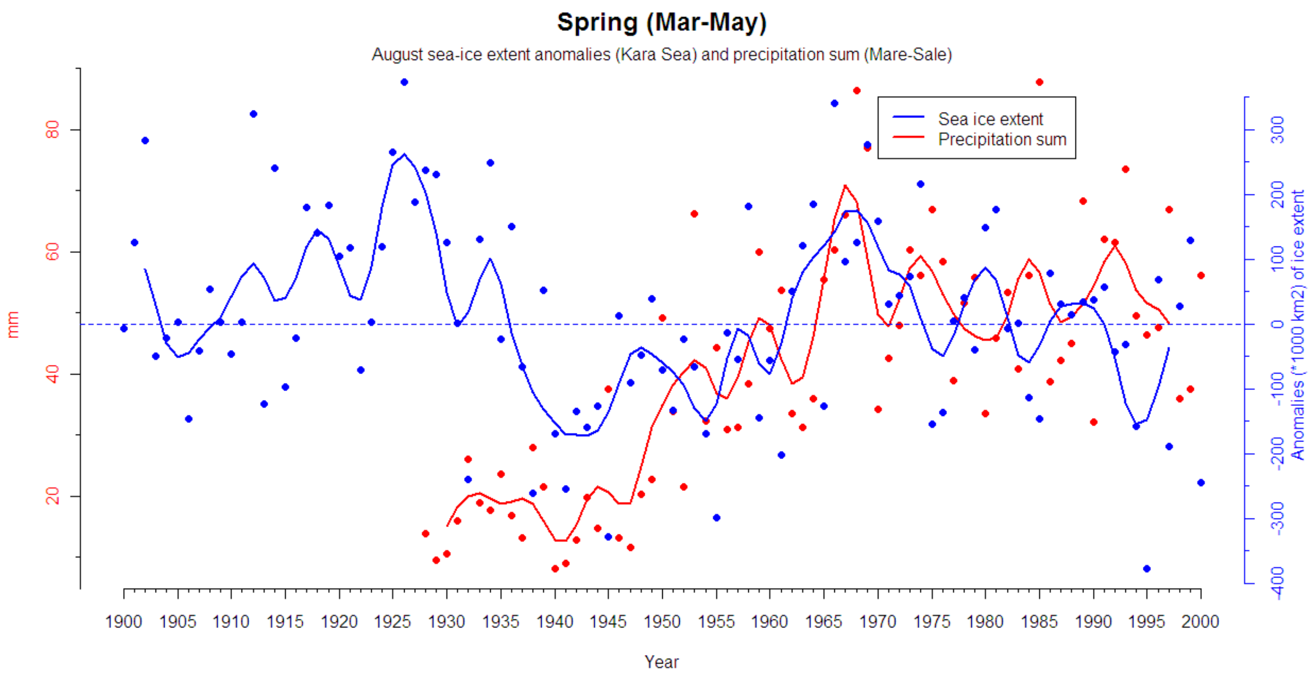


Figure 31: *Sea-ice extent and seasonal precipitation (autumn and winter) sum at the station Mare-Sale. 5 year Gauss filter.*



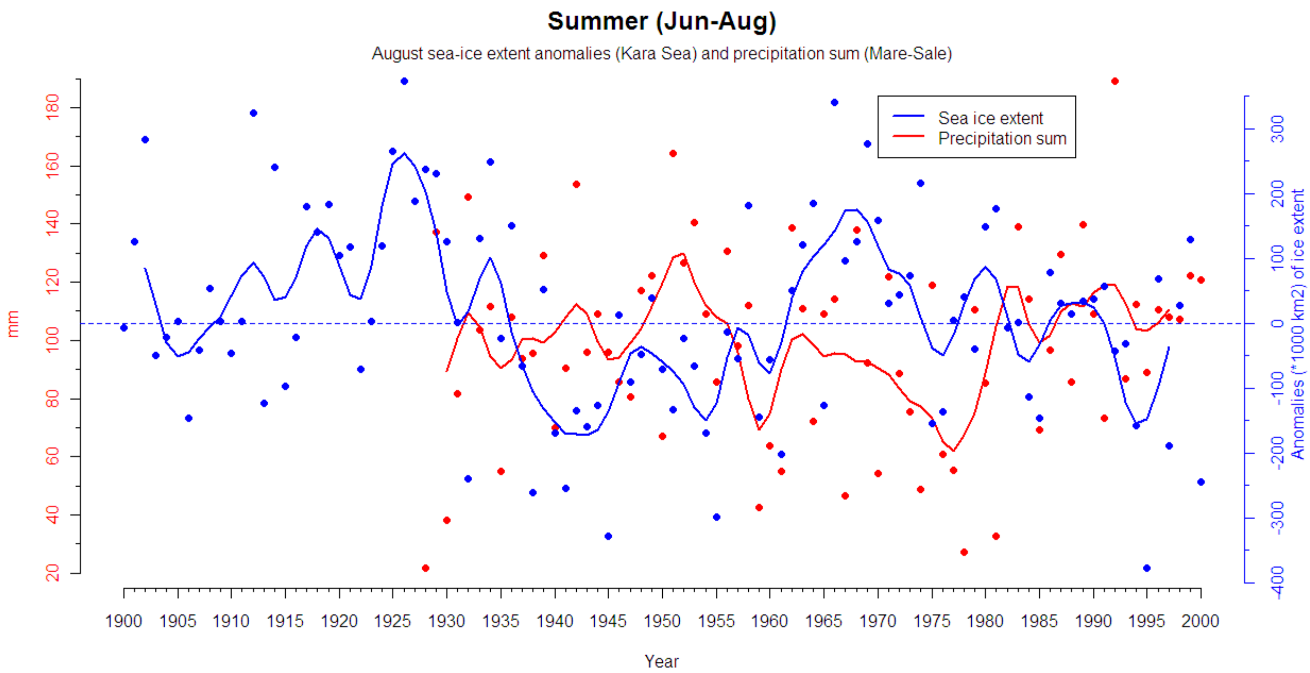


Figure 32: *Sea-ice extent and seasonal precipitation sum (spring and summer) at the station Mare-Sale. 5 year Gauss filter.*

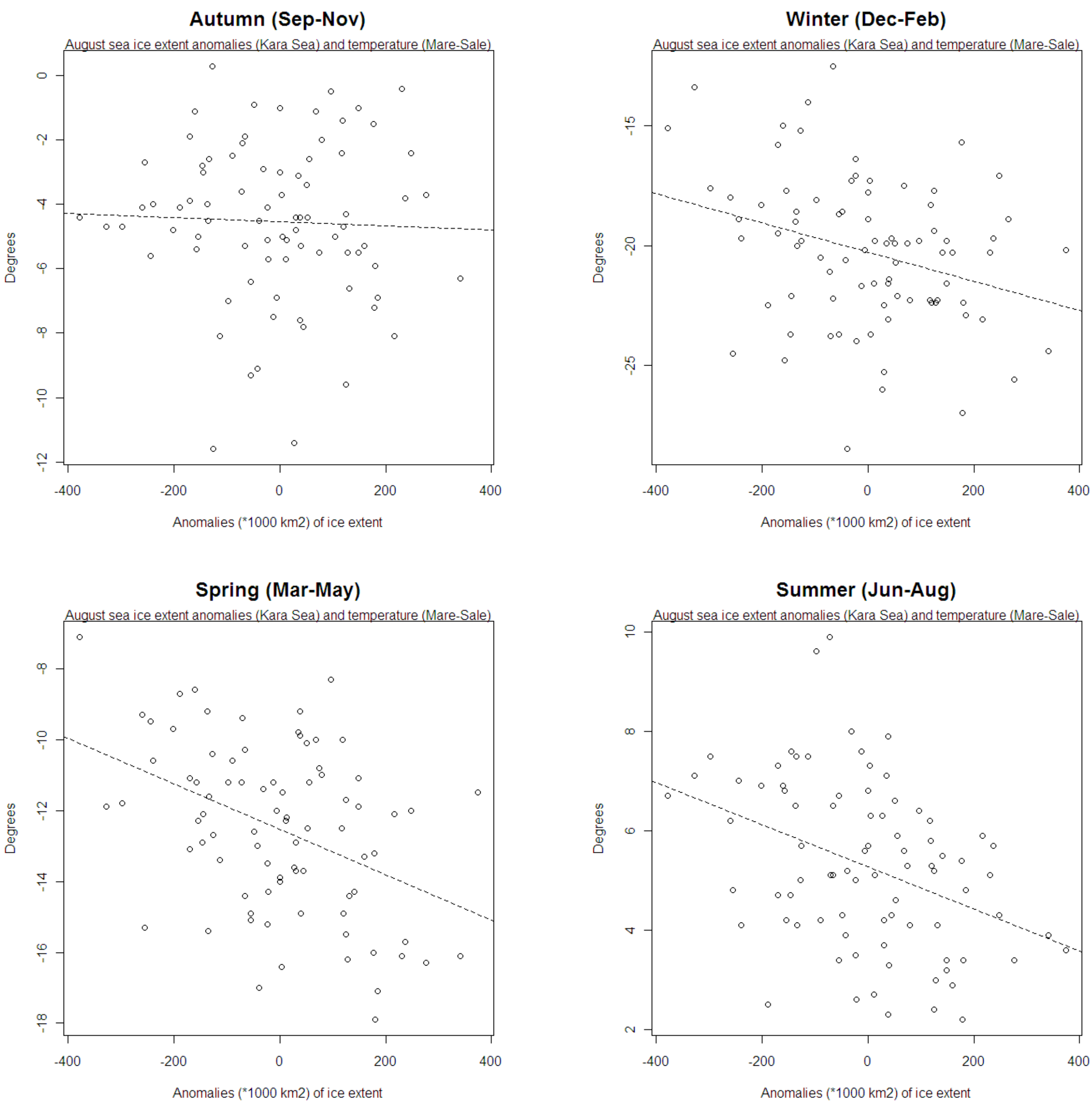


Figure 33: *Scatterplots of August sea ice extent anomalies and seasonal temperature.*

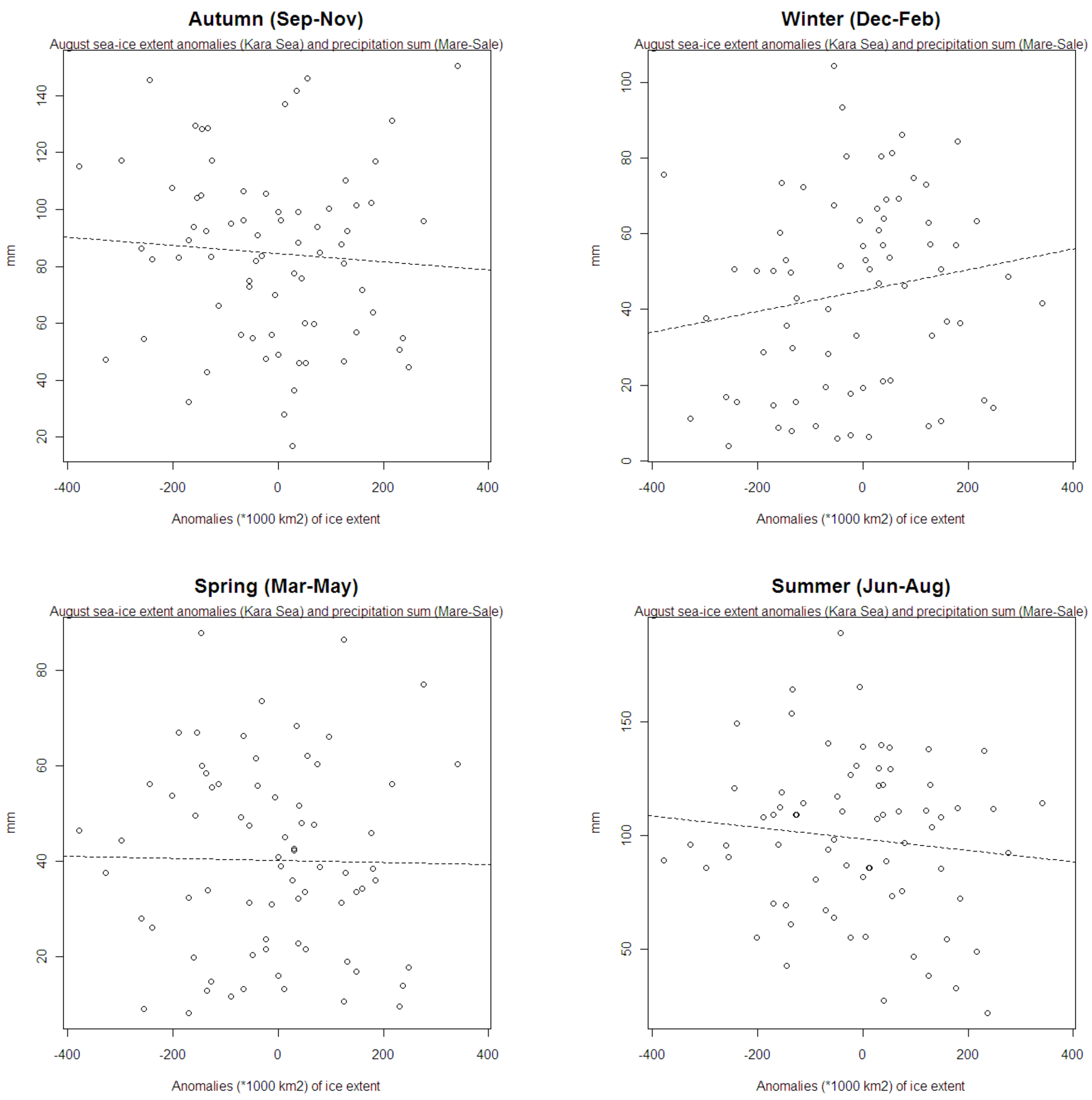


Figure 34: *Scatterplots of August sea ice extent anomalies and seasonal precipitation.*

5 Summary and conclusions

This report presents long-term climate trends from four meteorological stations of the Yamalo-Nenets AO (Mare-Sale, Tarko-Sale, Nadym and Salekhard). Long-term trends and decadal scale variability of air temperature, precipitation , snow season, cold season and growing season are described. The long term climate trends might influence the nomadic reindeer husbandry of the Yamalo-Nenets AO in future if these trends continue. The sea ice extent in the Kara sea might influence the climate and grazing conditions for reindeer in summer on the Yamal Penninsula.

Temperature

Salekhard is the only station with 100 years long temperature series. The linear trend in annual mean temperature from 1900-2008 for Salekhard is 0.05°C per decade (0.5°C per 100 years, not statistically significant). This is slightly less than the linear trend of 0.09°C per decade found for the Arctic (60°-90°N) for the period 1900-2003 (ACIA, 2005, p. 36). The linear trend in mean spring temperature is also statistically significant with an increase of 0.18°C per decade (1.8°C per 100 years). For all stations the decadal scale variability is similar, and it is large compared to the long-term trends. It mainly follows the periods described for the Arctic (60°-90° N) (ACIA, 2005, p. 35).:

1. Increasing temperatures from 1900 to the mid-1940s (often referred to as the “early 20th century warming”).
2. Decreasing temperatures from the mid-1940s until about the mid-1960s.
3. A “recent warming” from the 1960s to 2003. For Yamal this is shiftet to the period 1965/70s-1990/95s.

The coastal station Mare-Sale has the lowest mean annual temperature. Spring and summer are very cold months at Mare-Sale as compared to the other three stations. The proximity to the ocean and sea ice greatly influences the seasonal temperature.

Precipitation

Salekhard is the only station with 100 years long precipitation series. The linear trend in annual precipitation sum for Salekhard is 3.3% per decade (33% per 100 years, statistically significant at 1% level). This trend is larger than the linear trend of 1.4% per decade (14% per 100 years) found for the Arctic (60°-90°N) for the period 1900-2003 (ACIA, 2005, p.42). The long-term linear trends are positive and significant for all seasons in Salekhard (Table 9). Winter and spring have the largest positive trends with 5.3% and 4.5% increase per decade, respectively.

The differences in decadal variability between the individual stations are larger than for temperature in this region. The coastal station Mare-Sale, located by the Kara Sea, receives less precipitation than the other three stations during spring and summer. This might be related to higher frequency of convective precipitation in the inland areas than at the coast (differences in friction and turbulence over land areas, sea and sea ice).

Uncertainties are connected to precipitation measurements over time (relocation of stations, changes in instrumentation or observing practices, measurement errors because of undercatch or drifting/blowing snow).

Snow

Salekhard and Mare-Sale have long series of snow season duration data, respectively from 1885 and 1914. Generally the decadal-scale trends for the two stations are similar until around 1985.

A minimum period for the snow season duration appeared around 1945, corresponding to the end of the “early 20th century warming”. The snow season duration was the shortest during the last 100 years for Mare-Sale, but not for Salekhard which has occationally experienced just as short snow season duration in the last 15 years.

Cold season

The daily temperature series are too short to compute trends for the last 100 years. The decadal scale variability shows that a culmination period occurred around 1990-95 with the shortest cold periods since 1960s/1970s.

The coastal station Mare-Sale has a considerably larger number of days with daily mean temperatures below 0°C than the continental station Salekhard. However, the really cold days (daily temperatures below -30°C) are larger in number in Salekhard than in Mare-Sale. This may be explained by the close location of Mare-Sale to the ice-covered sea.

Growing season

Since 1965 the growing season is gradually prolonged at the Yamalo-Nenets AO. This increases the plant production and is therefore positive for the reindeer's summer pasture.

Sea-ice extent and climate at Mare-Sale

A comparison of time-series of August sea-ice anomaly data and seasonal temperature showed that the temperature decreases with increasing sea-ice extent (except during autumn). These correlations are weak. For precipitation, there is no correlation with sea ice extent. This relation is probably indirect and complex. More sophisticated analysis is needed to better understand how these factors (sea-ice extent in the vicinity of the station, atmospheric circulation, temperature, precipitation) influence each other.

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