Linking drought indices in the Atlantic sector of the High Arctic (Svalbard) to atmospheric circulation

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Abstract

Based on the long-term climatological data from Ny Alesund, Svalbard Airport – Longyearbyen and Hornsund Polish Polar Station, we undertook an analysis of drought indices on West Spitsbergen Island, Svalbard for the period 1979-2019.

The features and causes of spatio-temporal variability of atmospheric drought on Svalbard were identified, as expressed by the Standardised Precipitation Evapotranspiration Index (SPEI).

It was possible to indicate several-years long periods with the SPEI indicating a domination of drought or wet conditions. Long-term variability of annual and half-year (May-October) values of SPEI showed a prevalence of droughts in the 80-ties and in the first decade of the 21st century while wet seasons were frequent in the 90-ties and in the second decade of the 21st century. Seasonal SPEIs were characteristic of great inter-annual variability. In MAM and JJA droughts were more frequent after 2000; in the same period in SON and DJF, the frequency of wet seasons increased. The most remarkable changes in the scale of the entire research period were estimated for autumn where negative values of SPEI occur more often in the first part of the period and positive values dominate in the last 20 years.

The long-term course of the variables in subsequent seasons between 1979-2019 indicates strong relationships between the SPEI drought index and anomalies of precipitable water and somewhat weaker relationships with anomalies of sea level pressure.

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Key Points:

- Droughts prevailed in the 80-ties and in the first decade of the 21st century .
- Drought fluctuations have relationships with anomalies of precipitable water and with anomalies of sea level pressure.
- Dry conditions are associated with high pressure located between the Greenland Sea and the Barents Sea.

Abstract

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The features and causes of spatio-temporal variability of atmospheric drought on Svalbard were identified, as expressed by the Standardised Precipitation Evapotranspiration Index (SPEI).

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Keywords: Drought index, atmospheric circulation, SPEI, Svalbard, Arctic.

1 Introduction

Feedback mechanisms cause an Arctic amplification manifesting itself as an unprecedented increase in air temperature and liquid precipitation totals in polar regions as compared with temperate and tropical latitudes (Pithan and Mauritsen, 2014, IPCC 2019, Łupikasza et al. 2019a). These changes will likely continue in the future increasing both air temperatures and precipitation amount (IPCC 2021, Liu et al., 2021), facilitating changes in weather and climate-based drivers of glacier recession and thinning (van Pelt et al., 2019, Noel et al., 2020), permafrost degradation and defragmentation (Schaefer et al., 2014, Biskaborn et al., 2019, Strand et al., 2021), and increasing ecological risk for the whole ecosystem (Hinzman et al., 2013, Anderson et al., 2017, Owczarek et al., 2021).

The frequency and range of extreme climate events are thought to be the significant drivers of environmental changes (Walsh et al. 2020). The extreme events in the Arctic, such as abnormally dry conditions (drought) and heavy precipitation also significantly influence the fragile polar ecosystems. However, their environmental effects in warm/vegetation season are different from those in winter season.

Zang et al. (2020) studied variations of drought during the vegetation seasons in Northern Hemisphere and found that the duration and frequency of droughts decreased considerably from 1998 to 2015 and wetting trends were located mainly in high-latitude areas. He concluded that at the biome level, the wetting occurred mainly in the tundra, boreal forest or taiga, and temperate coniferous forest biomes, whereas the highly drought H-vulnerable areas were mainly located in the desert and xeric shrub-land biomes. However, climate extreme events in the Arctic fluctuate and occur alternately (Przybylak 2002, 2003, Reusen et al. 2019, Overland 2020, Wash et al. 2020).

In recent years research indicates heterogeneity in vegetation responses to climate change in the Arctic (Myers-Smithet al. 2020). While many Arctic regions have become greener since the 1980s, reflecting the positive response of tundra shrub species to warming and an increase in plant growth, satellite data show a decrease in plant productivity in many areas since the early 2000s (Phoenix and Bjerke 2016; Reichle et al. 2018). The number of sites showing spectral browning in satellite studies is increasing (Berner et al. 2020), which is in line with regional field studies showing recent declines in shrub growth due to drought stress. The role of precipitation has become increasingly important in recent years, as described for Greenland (Forchhammer 2017, Gamm et al. 2018), southern Spitsbergen (Owczarek and Opała 2016), Bear Island (Owczarek et al. 2021), Iceland (Phulara et al. 2022) or Siberia (Blok et al 2011). Some regional studies show that shrubs can benefits from drier conditions, which is possibly due to a higher availability of photo-assimilates under sunny conditions (Lehejcek et al. 2006). It should be noted that severe droughts evidenced in the Arctic, have affected not only tundra browning and reduction of productivity but also resulted in the mortality of populations of species (Breshears et al. 2005, Smith 2011, Bjerke et al. 2014, Opala-Owczarek et al. 2018). On the other hand, the conditions opposite to drought (long-lasting, heavy rain events and increased summer precipitation) influence hydrologic processes, soil thermal regime and stimulates permafrost thaw (Douglas et al. 2020). The increased precipitation leads to increase solifluction rate and mass movement activity, especially debris flow events (Owczarek et al. 2013, De Hass et al. 2015; Rouyet et al. 2021). In winter the environmental impact of deficit/abundant precipitation, which can also be expressed in the form of drought indices, is different. Negative anomalies of precipitation in winter result in a reduction of snow cover depth and diminished Snow Water Equivalent (SWE) which may further lead to a negative annual mass balance of the glaciers. On the other hand, the effect of positive anomalies of winter precipitation is the opposite, i.e. increased snow accumulation, higher values of SWE and positive mass balance. Moreover, higher snow cover in the non-glaciated areas increases the avalanche risk and deletes the onset of vegetation period and ground thaw (Isaksen 2007, Etzelmüller et al. 2011, Christiansen et al. 2013, Etzelmüller et al. 2011, Isaksen 2007, Kępski et al. 2017, Schuler et al., 2020).

Liquid precipitation in winter or winter thaws in the Arctic often described as "rain on snow events" (ROS), has negative consequences for the functioning of polar ecosystems. Rennert et al. (2009) reported that ROS events (the formation of icy layers) hamper the functioning of mammals during winter, whose populations fell as a result of restricted access to food. Bokhorst et al. (2016) and Opała-Owczarek et al. (2018) indicated the strong impact of ROS on vegetation due to the eroding effects of snow blizzards on ice-covered tundra. Łupikasza et al. (2019) found that an increase in the frequency of ROS events impacts both glacier mass balance and glacier dynamics and concluded that the total liquid precipitation during winter could be effectively stored in the glacier, contributing to 9% of the seasonal snow cover accumulation as a component of the glacier mass balance.

Serreze et al. (2015) stated that in Spitsbergen extreme events tend to occur when the region is influenced by a trough of low sea level pressure extending from the southwest, but some of the largest precipitation events can be associated with a 500hPa anomaly of geopotential height (positive over the Barents Sea and negative over Greenland) and positive anomalies in precipitable water with a stream extending even thousands of kilometres south into the subtropical Atlantic. This statement allows an assumption to be made that wet conditions expressed as drought indices are also related to anomalies in geopotential height and precipitable water over the North Atlantic. Thus, the hypothesis to investigate is that by contrast to conditions for extreme precipitation by Serreze et al. (2015), a deficit of atmospheric water and periods of dryness identified by negative values of the drought indices can also be explained by factors related to the distribution of baric field over the North Atlantic and regional circulation types.

This paper aims to recognize spatio-temporal variability of atmospheric drought impacting ecosystems on Svalbard and identify of atmospheric circulation patterns impacting wet and dry conditions (positive/negative values of drought indices) in the Atlantic sector of the High Arctic as represented by Svalbard.

2 Area, Data and Methods

The deficit or excess of precipitation is described by SPEI (Standardised Precipitation Evapotranspiration Index) by the WMO recommendations in relation to drought indices (WMO, 2016). The SPEI developed by Vicente-Serrano et al. (2010) and applied in numerous studies (Fischer et al. 2011, Núñez et al. 2014, Stagge et al. 2015) is calculated by normalization of climatic water balance (precipitation minus potential evapotranspiration) time series.

Based on the long-term climatological data from Ny Alesund (NyA), Longyearbyen - Svalbard Airport (LYR) and Hornsund - Polish Polar Station (HOR), we undertook an analysis of drought indices on West Spitsbergen Island, Svalbard for the period 1979-2019. The data were obtained from the Norwegian Centre For Climate services (https://seklima.met.no) and from the database published by Wawrzyniak and Osuch (2019, 2020).

Ny Alesund is a coastal north-westernmost station. Svalbard Airport (Longyearbyen) represents the middle and rather continental part of the island while Hornsund Polish Polar Station is located on the northern coast of the southernmost Hornsund fjord in Spitsbergen (Fig. 1). The stations are operating in accordance with operative measurement regulations and standards within the World Meteorological Organisation with the respective numbers 01007, 01008 and 01003.

Figure 1. Location of the study area
(By courtesy of the Norwegian Polar Institute, the details of the studied area are available at https://toposvalbard.npolar.no/?lat=78.12175&long=18.05456&zoom=1&layer=map).

Reanalysis products provided by the NOAA / ESRL Physical Sciences Laboratory, Boulder Colorado (http://psl.noaa.gov) were used to document the synoptic conditions over the North

Atlantic Ocean that determined the extreme pluviothermic episodes in Spitsbergen. The datasets used include composites (averages) of daily means or anomalies (deviation from long-term mean) of variables from the NCEP / NCAR Reanalysis. The plots were generated for the selected extreme values of SPEI. The following variables were used: sea level pressure, anomaly of air temperature, anomaly of 500 hPa geopotential height, omega index for 500 hPa explaining vertical motion of air mass and precipitable water anomaly between 1000-500 hPa. The influence of the regional atmospheric circulation on the SPEI values in Svalbard was assessed using the classification of atmospheric circulation types proposed by Niedźwiedź (2013, 2020).

Standardized Precipitation Evapotranspiration Index (SPEI) was calculated using observations of air temperature and precipitation from Ny Alesund, Longyearbyen (Svalbard Airport) and Hornsund. These meteorological variables allowed for the development of climatological water balance time series for the period 1979-2019. Potential evapotranspiration was estimated using the Hamon method based on daily air temperature and latitude of stations. A generalized Extreme Value probability distribution was fitted to the climatological water balance time series aggregated over a chosen period (annual, May-October, MAM, JJA, SON, and DJF). The same procedure was applied to all considered stations which further allowed for a comparison of the conditions between the stations. Trends in drought conditions were quantified with modified Mann-Kendall method.

The following SPEI classes were adopted: moderately wet 2 < SPEI ≤ 3; slightly wet 1 < SPEI ≤ 2; incipient wet spell 0.5 < SPEI ≤ 1; near normal -0.5 ≤ SPEI ≤ 0.5; incipient dry spell -0.5 > SPEI ≥ -1; slightly dry -1 > SPEI ≥ -2; moderately dry -2 > SPEI ≥ -3.

3 Results and Discussion

In the analyzed period 1979-2019, normal conditions (-0.5 ≤ SPEI ≤ 0.5) occurred on average per year from 36.6% at Svalbard Airport to 39.0% in Ny Alesund and 41.5% in Hornsund. MAM was a season with the greatest variation in average conditions, with 53.7% at Svalbard Airport and 29.3% at Ny Alesund and Hornsund. Cases of drought (SPEI <-0.5) most often occurred in the JJA season, i.e. 34.1% in Ny Alesund and 36.6% each in the other two stations. SON was the wettest season (with SPEI> 0.5), with 39.0% of frequency in Hornsund, 36.6% in Ny Alesund and 26.8% of frequency in Svalbard Airport, located in the interior of the island (Table I).

Table I. Frequency of the drought index SPEI (annual, May-October and quarter seasons MAM, JJA, SON, DJF) at Ny Alesund, Svalbard Airport and Hornsund (Spitsbergen) in the years 1979-2019.

	SPEI classes	Annual	May-Oct.	MAM	JJA	SON	DJF	month
NY ALESUND					**No of cases**			
moderately wet	*2 < SPEI ≤ 3*	0	1	0	1	1	2	x
slightly wet	1 < SPEI ≤ 2	8	4	8	4	5	4	x
incipient wet spell	0,5 < SPEI ≤ 1	5	10	7	10	9	6	x
near normal	0,5 ≥ SPEI ≥ -0,5	16	14	12	12	12	16	x
incipient dry spell	- 0,5 >SPEI ≥ - 1	4	4	7	7	8	5	x
slightly dry	- 1 > SPEI ≥ - 2	8	8	7	7	5	6	x
moderately dry	- 2 > SPEI ≥ - 3	0	0	0	0	1	1	x
					% of cases			
wet	SPEI > 0,5	31.7	36.6	36.6	36.6	36.6	30,0	x
near normal	0,5 ≥ SPEI ≥ -0,5	39.0	34.1	29.3	29.3	29.3	40,0	x
dry	SPEI < -0,5	29.3	29.3	34.1	34.1	34.1	30.0	x
MAX value/year		1.88/2016	2.48/2000	1.63/1990	2.15/2013	2.10/2016	2.08/2006	2.82/ V 2014
MIN value/year		-1.99/1995	-1.97/1995	-1.99/2018	-2.00/1985	-2.29/1995	-2.20/2000	-3.00/ IV 2006
SVALBARD AIRPORT					**No of cases**			
moderately wet	2 < SPEI ≤ 3	1	1	2	1	1	1	x
slightly wet	1 < SPEI ≤ 2	6	6	3	5	4	5	x
incipient wet spell	0,5 < SPEI ≤ 1	5	7	6	10	6	8	x
near normal	0,5 ≥ SPEI ≥ -0,5	15	17	22	10	19	13	x
incipient dry spell	- 0,5 >SPEI ≥ - 1	7	3	4	10	7	4	x
slightly dry	- 1 > SPEI ≥ - 2	7	7	2	4	3	9	x
moderately dry	- 2 > SPEI ≥ - 3	0	0	2	1	1	0	x
					% of cases			
wet	SPEI > 0,5	29.3	34.1	26.8	39.0	26.8	35.0	x
near normal	0,5 ≥ SPEI ≥ -0,5	36.6	41.5	53.7	24.4	46.3	32.5	x
dry	SPEI < -0,5	34.1	24.4	19.5	36.6	26.8	32.5	x
MAX value/year		2.33/1981	2.18/1981	2.49/1993	2.39/1981	2.76/2016	2.07/1996	2.84/ IV 1990
MIN value/year		-1.96/1998	-1.69/2009	-2.92/2006	-2.10/2007	-2.60/1995	-1.78/1987	-3.77/ IV 2006
HORNSUND					**No of cases**			
moderately wet	2 < SPEI ≤ 3	2	1	1	0	1	1	x
slightly wet	1 < SPEI ≤ 2	3	5	6	6	5	5	x
incipient wet spell	0,5 < SPEI ≤ 1	6	7	8	5	10	5	x
near normal	0,5 ≥ SPEI ≥ -0,5	17	13	12	15	12	17	x
incipient dry spell	- 0,5 >SPEI ≥ - 1	8	7	6	6	4	9	x
slightly dry	- 1 > SPEI ≥ - 2	3	7	6	9	8	3	x
moderately dry	- 2 > SPEI ≥ - 3	2	1	2	0	1	1	x
					% of cases			
wet	SPEI > 0,5	26.8	31.7	36.6	26.8	39.0	26.8	x
near normal	0,5 ≥ SPEI ≥ -0,5	41.5	31.7	29.3	36.6	29.3	41.5	x
dry	SPEI < -0,5	31.7	36.6	34.1	36.6	31.7	31.7	x
MAX value/year		2.29/2016	2.00/1994	2.31/1982	1.92/1994	2.16/2016	2.46/1996	2.81/ IV 1992
MIN value/year		-2.35/2019	-2.13/1987	-2.15/2019	-1.77/2017	-2.07/1983	-2.64/1988	-2.96/ IV 2006

Trends in drought conditions were quantified with modified Mann-Kendall method and are presented in Table II. Statistically significant changes were estimated for various periods depending on stations. An agreement in trend directions between Ny Alesund and Hornsund even in the case of insignificant trends. At these two stations (NyA, HOR) positive trends indicating wetter conditions dominated while in Longyearbyen (LYR) negative trends were significant indicating progressive dryness. Significant trends in the same direction at least at two stations were found in MAM, SON and DJF. The largest changes were estimated for autumn where negative values of SPEI occur more often in the first part of the period and positive values dominate in the last 20 years.

Table II. The results of trend analysis with modified Mann-Kendall method for SPEI.

	SPEI (change per decade)					
	Ny Alesund (NYA)		Svalbard Airport (LYR)		Hornsund (HOR)	
	Slope of trend	p-value	Slope of trend	p-value	Slope of trend	p-value
annually	0.3032	0.0817	-0.2724	0.0817	**0.3326**	0.0376
May-Oct	0.0566	0.6855	**-0.3650**	0.0147	**0.3033**	0.0398
MAM	-0.1637	0.2860	**-0.3601**	2.1962e-04	**-0.2285**	1.3323e-15
JJA	-0.2578	0.1082	**-0.3494**	0.0095	-0.0858	0.3399
SON	**0.3148**	0.0101	0.2005	0.1133	**0.4821**	8.5028e-04
DJF	**0.3801**	0.0066	0.1829	0.2487	**0.1820**	0.0065

The SPEI values were characteristic of big inter-seasonal variability (Fig. 2). In a particular season , all stations usually experienced the same conditions (dry or wet) but of various intensities. The seasons with extremely different conditions at the stations were rare.

In the studied period, it was possible to indicate several-year long periods with the SPEI of the same sign (plus or minus) indicating a domination of drought or wet conditions. Long-term variability of annual and half-year (May-October) values of SPEI showed a prevalence of droughts in 80-ties and the first decade of the 21st century while wet seasons were frequent in 90-ties and the second decade of the 21st century. Seasonal SPEIs were characteristic of great inter-annual variability. In MAM and JJA droughts were more frequent after 2000, in the same period in SON and DJF the frequency of wet seasons increased. The most remarkable changes in the scale of the entire research period were estimated for autumn where negative values of SPEI occur more often in the first part of the period and positive values dominate in the last 20 years.

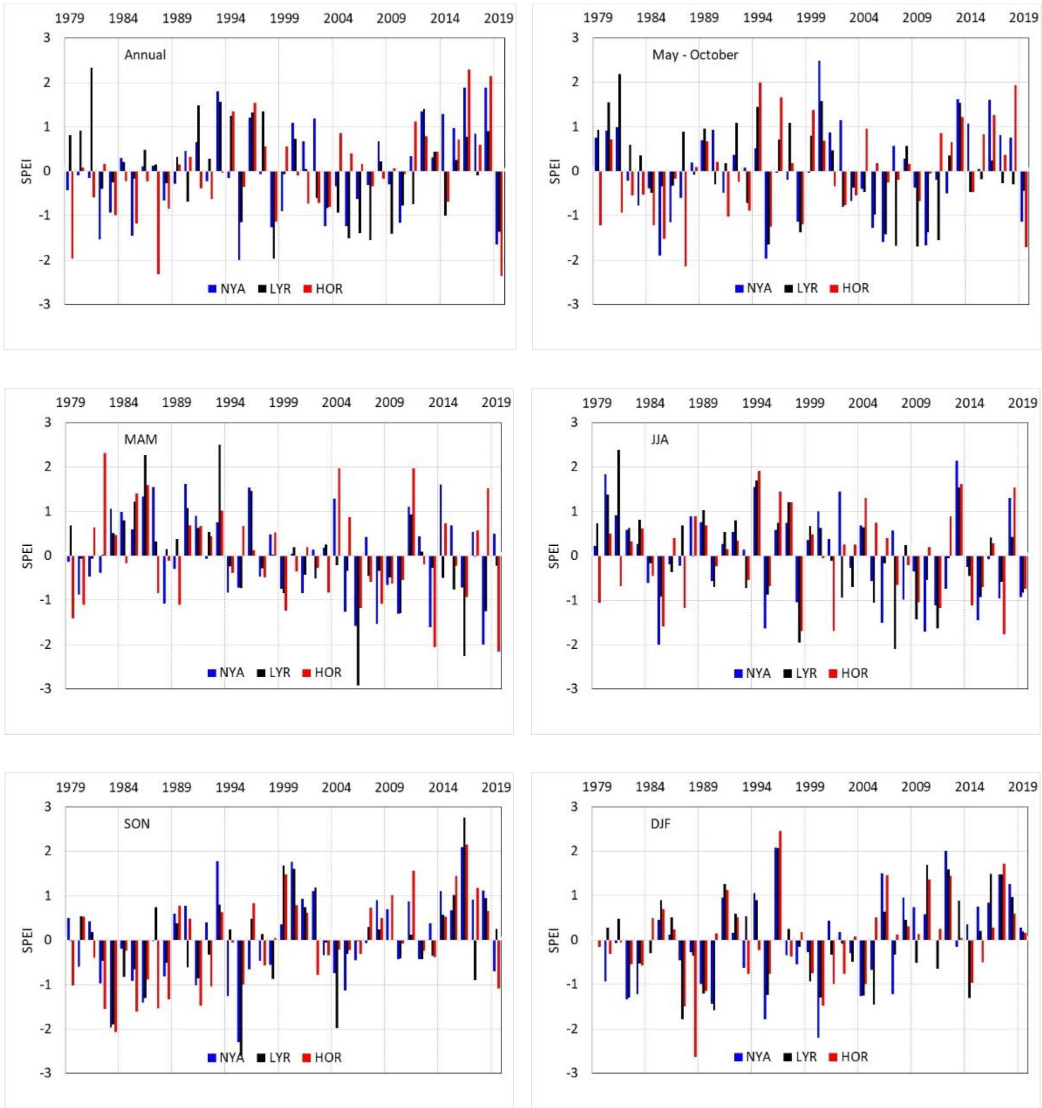


Figure 2. The Standardised Precipitation Evapotranspiration Index SPEI (annual, May-October and quarter seasons MAM, JJA, SON, DJF) at Ny Alesund, Longyearbyen and Hornsund, W Spitsbergen in the years 1979-2019.

Drought classes (DC): moderately wet 2 < DC ≤ 3; slightly wet 1 < DC ≤ 2; incipient wet spell 0,5 < DC ≤ 1; near normal -0,5 ≤ DC ≤ 0,5; incipient dry spell -0,5 > DC ≥ -1; slightly dry -1 > DC ≥ -2; moderately dry -2 > DC ≥ -3.

Extending the findings by Serreze et al. (2015) on conditions favouring the extreme precipitation occurrence in the Arctic, we assume that dry conditions identified with SPEI also depend on of the patterns of geopotential height and precipitable water over the Atlantic sector of the Arctic. The atmospheric conditions over the N Atlantic which occurred during months with the most extreme SPEI values in summer and winter in Ny Alesund, in Svalbard Airport/Longyearbyen and Hornsund are presented in Figures 3 and 4.

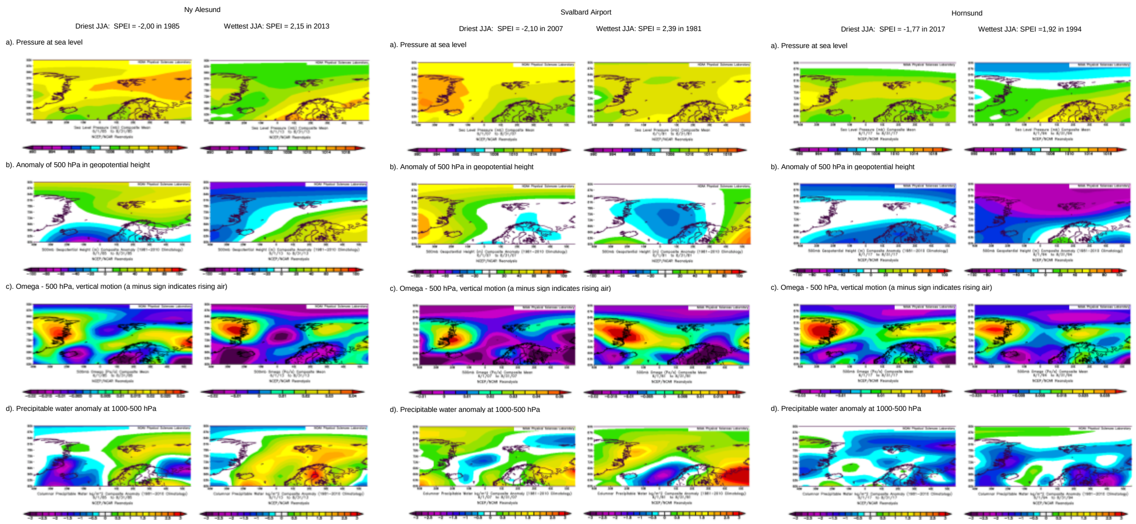


Figure 3. The atmospheric conditions over the N Atlantic formed in summer (JJA) the most extreme values of drought conditions in Ny Alesund, Svalbard Airport and Hornsund, W Spitsbergen. Image provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at http://psl.noaa.gov and submitted 10 December 2021.

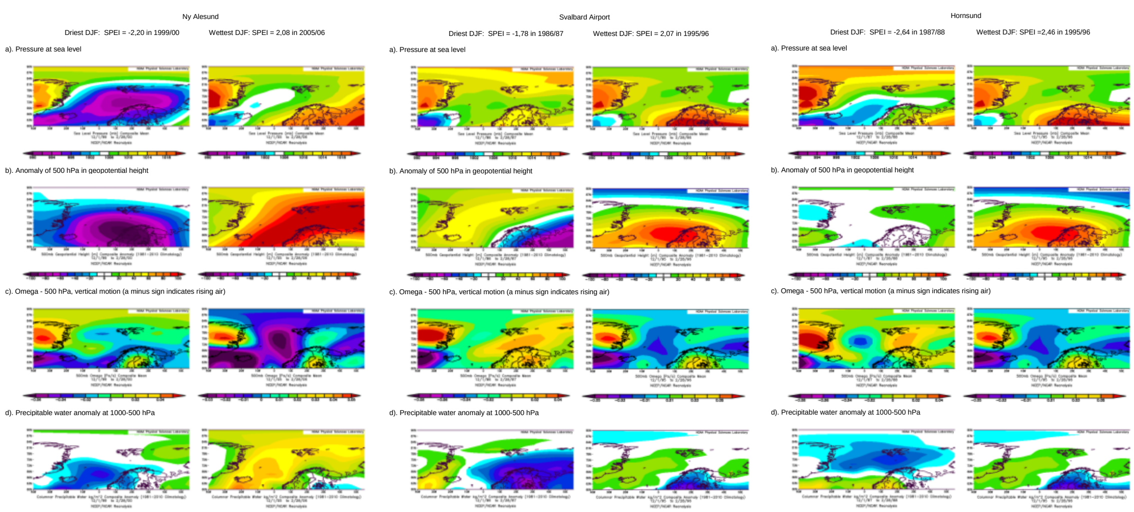


Figure 4. The atmospheric conditions over the N Atlantic formed in winter (DJF) the most extreme values of drought conditions in Ny Alesund, Svalbard Airport and Hornsund, W Spitsbergen. Image provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at http://psl.noaa.gov and submitted 22 January 2022.

Both extreme precipitation events and wet conditions expressed by high positive values of SPEI drought index depend on anomalies of 500 hPa geopotential height and precipitable water determined by the baric field over the North Atlantic. By contrast, a deficit of atmospheric water and periods of dryness are expressed by negative values of the drought indices. In DJF situations like these are formed over Svalbard when an area of high pressure develops with centres located over the Greenland and central Arctic reaching the Barents Sea (advection from the eastern sector) and blocking the transport of moisture usually associated with cyclonic advection of air masses from the S+SW sector (Fig. 4). In summer dry conditions are associated with the ridge of high pressure or extended area of increased pressure between the Greenland Sea and the Barents Sea. The dominating anticyclonic conditions block the intrusion of mid-latitude lows and related transport of wet air masses. Convection that favours extreme rainfall weakens under high-pressure conditions (close to 0 anomalies of Omega-500hPa) and the development of the anticyclonic conditions blocks the increase in precipitable water in the atmosphere and consequently inhibits the precipitation process and reduces the amount of rain. The low-pressure zone is then shifted to the south and stretches along the trajectories of the atmospheric fronts moving latitudinally from Iceland towards Scandinavia. The position of the lows is marked by a 500 hPa anomaly of geopotential height. The conditions favouring the occurrence of extreme precipitation which determine high SPEI values have been recognized by Serreze et al. (2015) for short-term states of the atmosphere. Such criteria averaged over relatively long JJA and DJF seasons, on the one hand, show a large spatial diversity, but on the other hand, the features proving their driving role become less clear. Therefore, in the next step, the circulation types are analysed as decisive for the occurrence of extremely dry and wet conditions in JJA and DJF, when the drought or water abundance is crucial for vegetation, ablation and melting of the active layer of permafrost (in JJA) or snowfall resources (in DJF) (Figure 5).

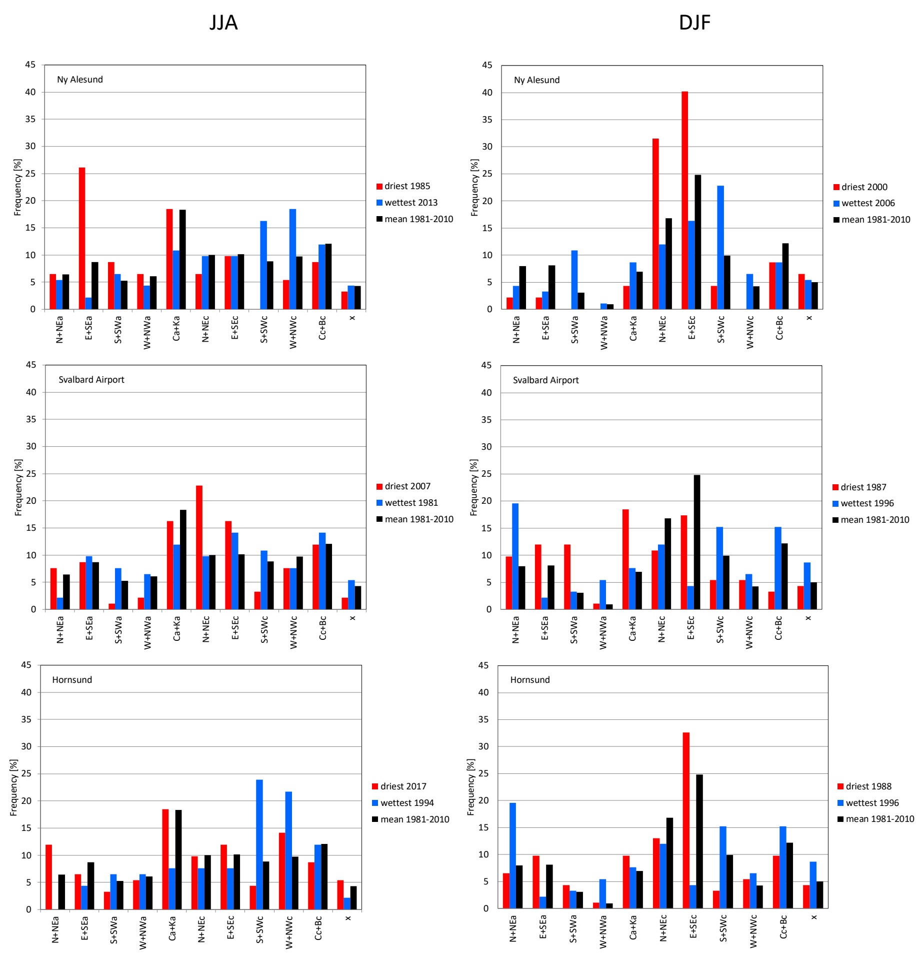


Figure 5. The frequency of atmospheric circulation types in the JJA and DJF seasons with the lowest and the highest values of SPEI vs climatic normal 1981-2010.

At analysed stations located in the distance of more than 200 km from each other, representing the northern, middle and southern parts of western Spitsbergen the most extreme values of drought conditions developed under the influence of various circulation types. However, it was possible to find some similarities in the patterns of circulation types frequency favouring extremely wet and dry conditions between Ny Alesund and Hornsund, both having more maritime climate than Longyearbyen. In summer (JJA) the driest episode in Ny Alesund occurred during anticyclonic circulation (a) with air advection from E+SE sector (type E+SEa) followed by the centre of high or high-pressure ridge over Svalbard (type Ca+Ka) that also favoured the occurrence of dry episodes in the south at Hornsund station due to more stable anticyclonic conditions or descending air in the Ca centre. Moreover, in Hornsund, dry episodes were related to advection of cold and dry air from N+NE (type N+NEa) under an influence of anticyclone which prevents convection, and to cyclonic types W+NW. According to previous studies type NWc insignificantly correlated with air temperature (Łupikasza and Niedźwiedź 2020) and is characteristic of low precipitation totals (Łupikasza 2013). In Longyearbyen dry conditions were primarily related to cyclonic circulation (c) from N+NE (type N+NEc) sector, followed by E+SEc and Ca+Ka types.

In Ny Alesund during extremely wet seasons cyclonic situation (c) with W+NW and S+SW advection dominated. The same types prevailed during drought in Hornsund; however, during the wettest episode in JJA 1994 the frequency of S+SWc type was higher than W+NWc. It is reasonable to state that it was S+SWc that generated extremely wet conditions at these stations. Many papers prove the increased precipitation over Svalbard during air advection from the southern sector (Łupikasza 2008, Łupikasza 2013, Dobler et al 2021).

In central Spitsbergen (Longyearbyen) JJA extremely wet conditions resulting from high frequency of cyclone centre or trough of low pressure (type Cc+Bc) which are both conductive to convection and an advection of warm and wet air masses from the E+SE sector.

In Ny Alesund, most dry winter (DJF) was due to cyclonic advection of cold and dry air from N+NE and warmer but also dry air from E+SE which intensified evaporation. The wettest DJF developed under cyclonic circulation (c) and increased compared to average, frequency of air advection from S+SW sector. Regardless of baric type, the air masses from S sector, particularly from SW are warmer and wetter than the arctic air. The driest conditions in the central part of Svalbard appeared during the existence of the ridge of high pressure or high with its centre located over Svalbard. (type Ca+Ka) and, like in the north, during cyclonic circulation (c) from E+SE sector. In that part of Svalbard, and in the south (Hornsund), high values of SPEI were favoured by S+SWc type (the occurrence of precipitation) and the anticyclonic N+NEa type (low evaporation due to low temperatures). Interestingly, in both locations, the frequency of N+NEa type was high during the extremely wet episode in 1996.

Concluding, averaged over the JJA and DJF seasons the mean state of the atmosphere during extremely dry conditions indicates that only the anticyclonic conditions, particularly the K+Ca type and air advection from the N sector and negative anomalies of precipitable water are decisive for dry conditions in contrast to wet conditions which are driven by positive anomalies of precipitable water and cyclonic conditions. These results were proved by the frequency of regional circulation types during the JJA and DJF seasons with the lowest and the highest values of SPEI. Figure 6 shows long-term variability in the anomalies of sea level pressure and precipitable water for summer (JJA) and winter (DJF) seasons in the northern part of the research area (Ny Alesund), central (Longyearbyen) and southern part of Svalbard (Hornsund).

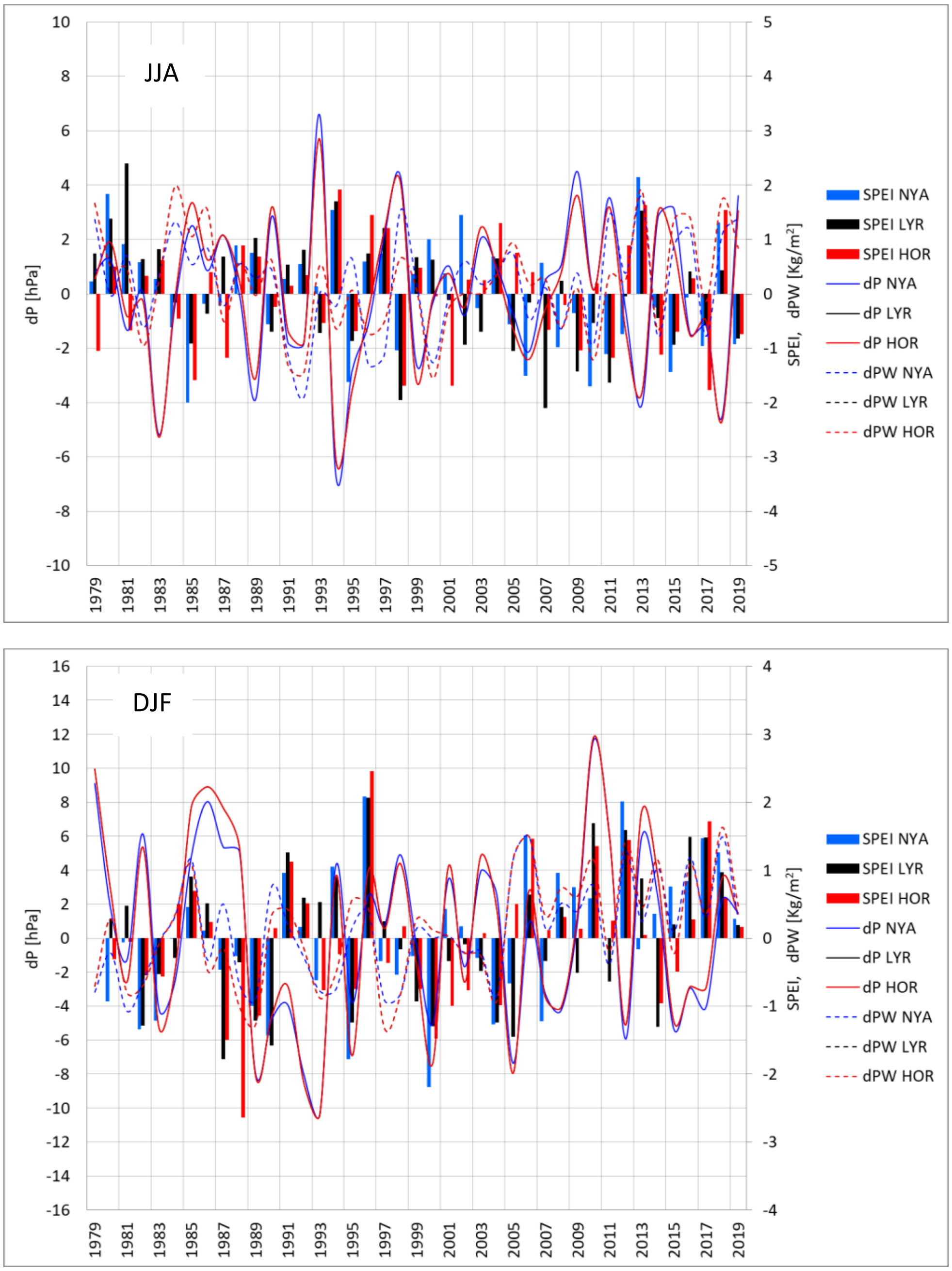


Figure 6. SPEI in summer (JJA) and winter (DJF) and anomalies of mean atmospheric pressure and precipitable water (vs climatic normal 1981-2010) in Ny Alesund (NYA), Longyearbyen (LYR) and Hornsund (HOR). Image provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at http://psl.noaa.gov and submitted 28 January 2022.

The long-term course of the variables in subsequent seasons between 1979-2019 indicates strong relationships between the SPEI drought index and anomalies of precipitable water (PW) and somewhat weaker relationships with anomalies of sea level pressure. As long as the differences in the anomalies of atmospheric pressure between the stations can be considered as insignificant, the anomalies of precipitable water during dry conditions in Ny Alesund differed from those in Longyearbyen and Hornsund both having similar patterns of atmospheric conditions favouring droughts occurrence.

During most of the analysed period the dry and wet situations occurred alternatively as mesoscale phenomena appearing simultaneously over the entire Spitsbergen in particular years (Figure 2 and Figure 6). However, in the case of several years the extreme conditions were found in the same year, e.g. drought in the north wet conditions in the south or opposite. In the period 1979-2019 the months with uniform wet-dry conditions constituted from 39% to 41.5% cases for both seasons, while the contrast conditions were represented by one-third cases (24.4%-26.8%) (Table III).

Table. III. Years with extreme SPEI values in July, summer and winter in Ny Alesund, Longyearbyen and Hornsund.

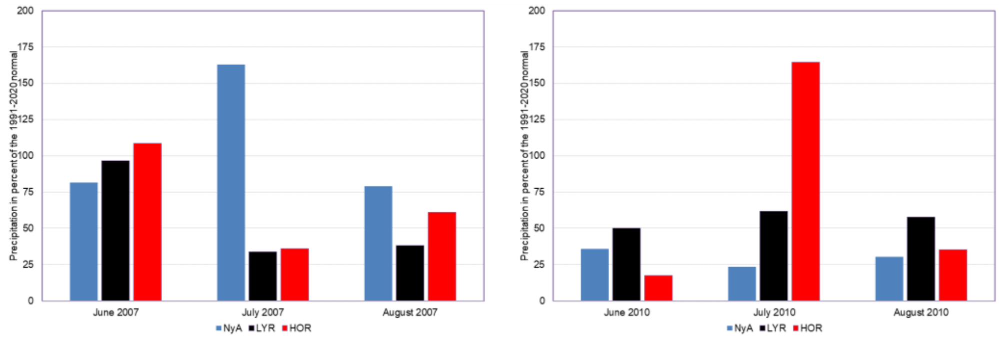
SPEI JULY				SPEI JJA				SPEI DJF			
Year	NyA	LYR	HOR	Year	NyA	LYR	HOR	Year	NyA	LYR	HOR
1986	-0.54	-0.28	1.07	1979	0.23	0.74	-1.05	1980	-0.93	0.28	-0.31
1991	0.94	-0.03	-0.66	1987	-0.22	0.68	-1.17	1993	-0.62	0.53	-0.77
1992	0.34	-0.10	-0.99	2000	1.00	0.63	-0.05	1994	1.05	0.89	-0.23
2001	-0.65	0.24	-0.86	2001	0.38	-0.11	-1.69	2001	0.43	-0.33	-0.99
2002	1.27	-0.78	-0.42	2002	1.45	-0.94	0.26	2005	-0.67	-1.45	0.51
2007	1.03	-1.34	-0.75	2005	-0.56	-1.05	0.75	2007	-1.22	-0.33	0.12
2008	-0.59	0.72	-0.35	2006	-1.51	-0.16	0.4	2009	0.75	-0.51	0.13
2010	-1.24	-0.26	0.77	2007	0.57	-2.1	-0.66	2013	-0.16	0.88	0.04
2012	-0.74	0.23	0.32	2008	-0.99	0.24	-0.21	2014	0.35	-1.3	-0.96
2017	0.38	0.16	-0.85	2010	-1.7	-0.54	0.2	2015	0.76	0.2	-0.5
				2012	-0.74	-0.04	0.89				

For two reasons special attention has been focused on SPEI values for the summer season (JJA) and its individual summer months. It was assumed that the analysis of atmospheric conditions on a monthly scale help to explain spatial variations in wet/dry conditions. Moreover, the analysis on a monthly scale enables description of the relationships between SPEI and tundra vegetation. To do so, July was selected when the intense development of vegetation is not limited by snow cover like in June.

The contrasts in wet/dry conditions over Svalbard are well represented by the summers of 2007 and 2010. In the summer 2007, particularly in July the northern part of Svalbard (Ny Alesund) with slightly wet conditions (SPEI = 1.03) strongly contrasted with the drought that appeared in the central (Longyearbyen, SPEI: -1.34, slightly dry) and south-western Svalbard (Hornsund, SPEI = -0.75). In July 2010 the situation was opposite i.e. drought in the north (Ny Alesund, SPEI = -1.24) and incipient wet spell in the vicinity of Hornsund (SPEI = 0.77), and near normal conditions in Longyearbyen (SPEI = -0.26). Figure 7 illustrates the precipitation differences between analysed stations in the summer seasons 2007 and 2010. The atmospheric conditions over Svalbard during contrasting conditions in the summer July 2007 and 2010 are presented in Figure 8.

2007 **2010**

Precipitation in percent of the 1991-2020 normal



Monthly precipitation and number of days with precipitation 1 ≥ mm

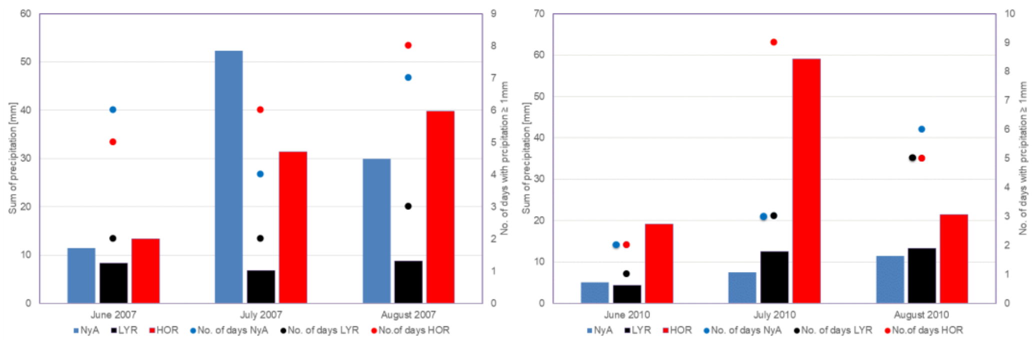
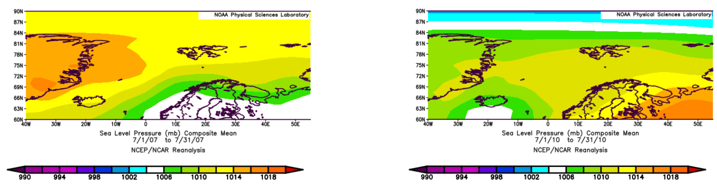


Figure 7. Monthly precipitation in summer seasons 2007 and 2010 in Ny Alesund, Longyearbyen and Hornsund (Figure based on the data from the Norwegian Centre For Climate services (https://seklima.met.no) submitted 24 of February 2022).

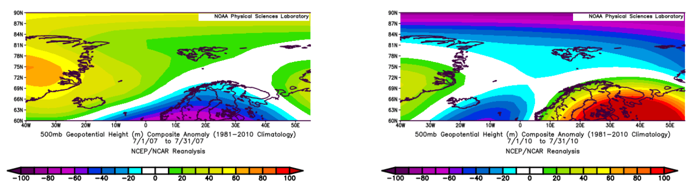
July 2007 | July 2010

SPEI: NYA 1,03; LYR -1,34; HOR – 0,75 | SPEI: NYA -1,24; LYR -0,26; HOR 0,77

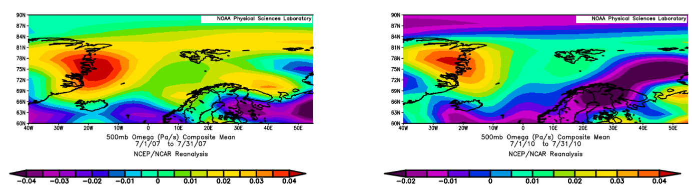
a). Pressure at sea level



b). Anomaly of 500 hPa in geopotential height



c). Omega - 500 hPa, vertical motion (a minus sign indicates rising air)



d). Precipitable water anomaly at 1000-500 hPa

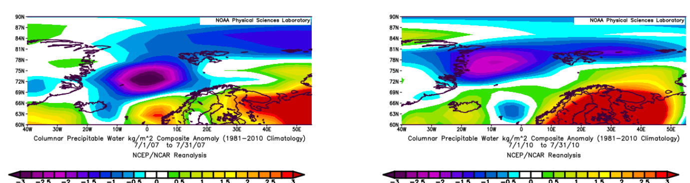


Figure 8. The atmospheric conditions over the N Atlantic formed in July 2007 and 2010 the most extreme contrasts of drought conditions between Ny Alesund, Svalbard Airport and Hornsund, W Spitsbergen. Image provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at http://psl.noaa.gov and submitted 11 of February 2022.

Contrasts of SPEI in July 2007 and 2010 were due to diverse precipitation in the north compared to the south part of Svalbard. The total July precipitation in Ny Alesund in 2007 exceeded 160% of 1991-2020 average, while in Longyearbyen and Hornsund the precipitation totals reached 33-35% of the average. In 2010 situation was opposite i.e. in Hornsund the total precipitation in July reached 164% of the climatic norm, in Longyearbyen - 62%, and in Ny Alesund the total reached only one fourth of the norm (23.4%) calculated as average from the period 1991-2020.

Slightly wet conditions in northern Svalbard (Ny Alesund) and simultaneously slightly dry conditions in the central part and incipient dry spell in the south developed under an influence of the ridge of high pressure related to the well-expanded high with its centre over the southern part of Scandinavian Peninsula. Such a distribution of air pressure forced the air masses to inflow over central and southern Svalbard from over the Barents Sea causing negative anomalies of perceptible water over the Greenland Sea. At the same time, in the northern part of Svalbard is under an influence of anticyclone circulation prevailed the conditions that favoured the development of air temperature inversions and low stratiformis cloudiness and drizzle.

4 Conclusions

In the analyzed period 1979-2019, normal conditions ($-0.5 \leq$ SPEI ≤ 0.5) occurred on average per year from 36.6% at Svalbard Airport to 39.0% in Ny Alesund and 41.5% in Hornsund. MAM was a season with the greatest variation in average conditions, as 53.7% at Svalbard Airport and 29.3% at Ny Alesund and Hornsund. Cases of drought (SPEI <-0.5) most often occurred in the JJA season, i.e. 34.1% in Ny Alesund and 36.6% each in the other two stations. SON was the wettest season (with SPEI> 0.5), with 39.0% of frequency in Hornsund, 36.6% in Ny Alesund and 26.8% of frequency in Svalbard Airport, located in the interior of the island.

In the studied period, it was possible to indicate several-year long periods with the SPEI of the same sing (plus or minus) indicating a domination of drought or wet conditions. Long-term variability of annual and half-year (May-October) values of SPEI showed a prevalence of droughts in 80-ties and in the first decade of the 21st century while wet seasons were frequent in 90-ties and in second decade of the 21st century. Seasonal SPEIs were characteristic of great inter-annual variability. In MAM and JJA droughts were more frequent after 2000; in the same period in SON and DJF the frequency of wet seasons increased. The most remarkable changes in the scale of the entire research period were estimated for autumn where negative values of SPEI occur more often in the first part of the period and positive values dominate in the last 20 years.

During most of the analysed periods the dry and wet situations occurred alternatively as mesoscale phenomena appearing simultaneously over the entire Spitsbergen in particular years. The extreme conditions occurred for various years at each station. In the NW part of Spitsbergen (Ny Alesund) the driest summer appeared in 1998 (SPEI -2.00), while an extremely wet summer was that in in 2013 with SPEI value of -2.15. In the central part of Spitsbergen (Svalbard Airport/Longyearbyen) the extreme summers occurred in 2007 with drought index equal to -2.10 and in 1981 with the highest ESPI value of 2.39. In Hornsund representing the South of Spitsbergen, the driest summer season (JJA) was that in 2017 with SPEI value of -1.77 and the wettest JJA occurred in 1994 with SPEI equal to 1.92. In Ny Aalesund the driest winter (DJF) occurred in 1999/00 with SPEi -2.20. The winter season 005/06 was extremely wet. In Longyearbyen the extreme seasons were in 1986/87 (SPEI -1.78) and 1995/96 (SPEI 2.07). In the south of Spitsbergen, in Hornsund extremely wet winter overlapped with that in Longyearbyen (1995/96 with SPEI 2.07). During the driest winter of 1987/88 SPEI reached -2.64.

Both extreme precipitation events and wet conditions expressed by high positive values of SPEI drought index depend on anomalies of 500 hPa geopotential height and precipitable water determined by the baric field over the North Atlantic. By contrast, a deficit of atmospheric water and periods of dryness are expressed by negative values of the drought indices. In DJF situations like these are formed over Svalbard when an area of high pressure develops with centres located over the Greenland and central Arctic reaching the Barents Sea (advection from the eastern sector) and blocking the transport of moisture usually associated with cyclonic advection of air masses from the S+SW sector. In summer dry conditions are associated with ridge of high pressure or an extended area of increased pressure between the Greenland Sea and the Barents Sea.

Averaged over the JJA and DJF seasons the mean state of the atmosphere during extremely dry conditions indicates that only the anticyclonic conditions, particularly the K+Ca type and air advection from the N sector and negative anomalies of precipitable water are decisive for dry conditions in contrast to wet conditions which are driven by positive anomalies of precipitable water and cyclonic conditions. These results were proved by the frequency of regional circulation types during the JJA and DJF seasons with the lowest and the highest values of SPEI.

At analysed stations located in a distance of more than 200 km from each other, representing the northern, middle and southern part of western Spitsbergen the most extreme values of drought conditions developed under the influence of various circulation types. However, it was possible to find some similarities in the patterns of circulation types frequency favouring extremely wet and dry conditions between Ny Alesund and Hornsund, both having more maritime climate than Longyearbyen.

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