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# LONG-TERM VARIABILITY OF PRECIPITATION FORM IN HORNSUND (SPITSBERGEN) IN RELATION TO ATMOSPHERIC CIRCULATION (1979–2009)

**Abstract**. The paper discusses the impact of the atmospheric circulation on the long-term variability of liquid, mixed and solid precipitation. The three precipitation forms were characterised by their totals, the number of days when they prevailed, and the contribution of each to the overall precipitation totals. Trends, as a background to further analysis, were calculated with regard to each characteristic of each precipitation form. The most significant increases were recorded in the contribution of liquid precipitation to the overall precipitation totals in September and in the mixed precipitation totals in December and November. Arctic Oscillation (AO) was found to have only a minor influence on the long-term variability of precipitation characteristics. The AO phase could to some degree account for the observed variation in the number of days with liquid precipitation. On the other hand, the direction of the local advection could account for considerably more of this variability and also the variability in liquid precipitation totals.

**Key words:** precipitation trends, solid precipitation, liquid precipitation, Arctic Oscillation, circulation patterns

## Introduction

Days with snowfall account for 79% of all days with precipitation in a year at Hornsund. Mixed and liquid precipitation forms are much rarer at 13% and 8% of days in a year, respectively (Łupikasza 2003). The form of the atmospheric precipitation is strictly dependent on air temperature and this dependency varies geographically (Lauscher 1954; Cehak-Trock 1958; Hess 1965; Przybylak 2002; Førland and Hanssen-Bauer 2003; Łupikasza 2008). At Hornsund snowfall is most frequent on days with temperatures ranging from -11.0°C to 0.0°C. Liquid precipitation prevails when the average daily temperature ranges between 3.0°C and 7.0°C. Mixed precipitation is most likely on days with an average daily temperature between 0.0°C and 2.0°C (Łupikasza 2008). Snowfall is considered an important indicator of climate change due to the clear relationship found between air temperature and the precipitation form. As temperature rises the frequency of snowfall can be expected to decline and liquid precipitation can be expected to increase. The analysis of the frequency of precipitation forms is of great importance in the Arctic, which, according to both observations and climate model simulations, is very sensitive and vulnerable to climate change (Przybylak 1996, 2000). The latest investigation by Przybylak (2007) shows an abrupt rise in surface air temperature which occurred in the mid-1990s and was most pronounced in autumn and spring (Przybylak 2007). Alongside temperature, atmospheric circulation, which plays a key role in determining the weather in Spitsbergen (Niedźwiedź 1993, 2001), is a factor that determines the frequency, amount and long-term variability of the precipitation form. There is, however, no published research available on this effect. What is known is that atmospheric circulation has a significant impact on the frequency and amount of precipitation regardless of its form. At Hornsund the highest daily precipitation totals are recorded most frequently during the advection of warm and humid air from the SW and S when the archipelago is under the influence of a low pressure system (Łupikasza and Niedźwiedź 2002; Niedźwiedź 2002; Marsz and Styszyńska 2007).

The aim of this study is to identify the impact of the macro-scale and regional atmospheric circulation on the occurrence and amount of precipitation forms and on the long-term variability of these characteristics.

## Data and methods

The study used daily precipitation totals and records of meteorological phenomena (past and present weather records) from Hornsund relating to the period 1979–2009. The term ’present weather’ here refers to weather phenomena present at the time of the observation. ‘Past weather’ is used to describe significant weather events occurring during the previous hour, but not occurring at the time of the observation (WMO 2006). Most of the data were sourced from the annual meteorological records for Hornsund (Miętus 2000–2001, Institute of Geophysics 2001, 2003). The data from August 1981 to August 1982 come from the private archive of Dr. Mieczysław Sobik of the University of Wrocław. The data from 2001 were provided in digital format by the Institute of Geophysics of Polish Academy of Sciences. There are small gaps in the precipitation database compiled for the purposes of the study; there are omissions on 4, 7, 9 and 18 July 1979 and between 1 and 26 July 1981. Moreover, no information exists on the occurrence of meteorological phenomenon between 1 August 1981 and 15 August 1982.

Three forms of precipitation were considered: liquid (primarily rain or drizzle), mixed (sleet or rain and snow) and solid (primarily snow). The daily precipitation form was determined using records of meteorological phenomena (mentioned in past and present weather records). Additional criteria included the average, maximum and minimum daily temperatures at 200 cm above ground level. Where no record of meteorological phenomena was available, only the temperature criteria were applied and hence the data during this period may include a certain degree of inaccuracy as to the precipitation form, especially in the transitional months. The transitional months are those at the end and at the beginning of the warm and cold seasons, when the frequency of mixed precipitation is high due to air temperatures which are lower than in the mid-warm season and higher than in the mid-cold season (Apr, May, Sep, Oct).

Relationships between each of the precipitation forms and the atmospheric circulation were determined using monthly values of the Arctic Oscillation (AO) Index (Thompson and Wallace 1998), representing the macroscale circulation, and with a calendar of circulation types by Niedźwiedź (2009), representing atmospheric circulation on a regional scale. The AO is the changing balance of atmospheric pressure between northern mid, and high latitudes. The AO index is said to be negative when there is relatively high pressure over the polar region and lower than normal pressures in the mid latitudes; the positive phase is when the pressures are reversed (Strangeways 2007). Monthly values of AO were taken from National Oceanic and Atmospheric Administration webpage (http://www.cpc.noaa.gov/products/...). These were calculated by applying the Empirical Orthogonal Function (EOF) to the mean monthly 1000-hPa height anomalies north of

20°N latitude. The loading pattern of AO is defined as the first leading mode from the EOF analysis of monthly mean height anomalies at 1000-hPa. The circulation calendar by Niedźwiedź (2009) comprises 21 circulation types defining air mass advection (e.g. N – northern, NE – north-eastern, E – eastern, etc.) and air pressure system (a – anticyclone, c – cyclone). Sixteen of the types feature an identified direction of air mass flow (e.g. Nc, NEc, Na, NEa etc.), while four are non-advection types (Ca – high centre, Ka – anticyclonic wedge or ridge of high pressure, Cc – centre of low, Bc – trough of low pressure with different directions of air flow and frontal system in the axis of trough). The final type is an unclassified type marked as x.

The study is divided into three main sections. The introductory section looks at general trends of the three characteristics of the precipitation forms studied, i.e. the number of days with each precipitation form (including trace one, precipitation day: 06AM:06AM), their totals and the contribution of each form to the overall precipitation total. The aim of this section is indirectly linked to global climate changes. Clear long-term trends in the characteristics of the precipitation forms studied may be evidence for changes in the climate recently taking place in Hornsund (Przybylak 2000, 2007). The monthly and seasonal trends of these characteristics were calculated for the entire study period and for arbitrarily defined sub-periods: 1979–2000, 1979–2001, 1979–2002, …, 1979–2009. With this approach it was possible to establish the stability of both the direction of the trends and their statistical significance, both being highly dependent on the initial and final values in each time-series. The overall trends were determined using a linear least squares method. The significance of trends was tested with a *t* test and a Mann-Kendall test (Mann 1945; Kendall 1970; Mitchell et al. 1966; Sneyers 1999). The statistical significance of trends in precipitation and its characteristics is usually lower than that of trends in other climate elements due to its large spatial and temporal variability. Therefore, the significance level of $\alpha=0.2$ was used in this study (Rapp 2000; Łupikasza 2010). The t-test indicates the existence or absence of a linear trend in the characteristics of precipitation forms whereas the Mann-Kendall trend delivers information on a monotonic decrease or increase of the character of precipitation forms. The statistical significance proved by both methods delivers evidence for robust changes in characteristics under investigation. Trends were expressed as a percentage of the long-term average (1979–2009) of each characteristic. In this way so-called relative trends were produced, which could be compared regardless of the units in which the actual characteristics studied were expressed.

The last two sections are devoted to the influence of atmospheric circulation on the long-term variability of the precipitation forms. The second section focuses on correlations between the long-term variability of the said characteristics in each form of precipitation and the AO and identifies the influence of the AO phase on these characteristics. The final section assesses which of the 21 regional circulation types have the greatest impact on the long-term variability of the precipitation forms. The influence of circulation on the long-term variability of the characteristics was determined by calculation of correlation coefficients between the frequency of each of the circulation types and seasonal values of the characteristics of precipitation forms (the number of days and totals). Two correlation methods were used: the Pearson product-moment correlation coefficient (Pearson's correlation) and the non-parametric Spearman's rank correlation coefficient. It was assumed that the influence of the circulation factor on the long-term variability of the characteristics of the precipitation forms was regarded as strongly documented when both of the coefficients were statistically significant at α≤0.05; where the statistical significance level of the two dependency measures ranged between α=0.2 and α=0.05, the influence of atmospheric circulation on the long-term variability of precipitation forms was regarded as weak.

The calculations were conducted in a seasonal framework and on a monthly basis within the seasons. The seasons were defined in relation to the occurrence of precipitation forms (Fig. 1). A solid precipitation season is therefore defined as a period from October to May and a liquid precipitation

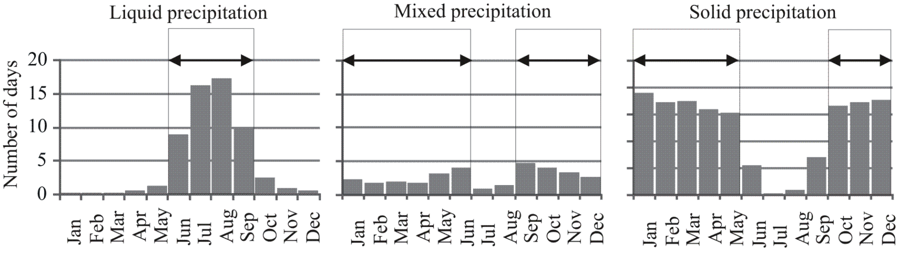


Fig. 1. Monthly number of days with liquid, mixed and solid precipitation at Hornsund. Bars and arrows show precipitation seasons, which are different for different precipitation types

season lasts from June to September. The mixed precipitation, observed at Hornsund throughout the year, was studied either on an annual basis or on a monthly basis separately for the solid precipitation seasons (mixed precipitation of the cool season) and for the liquid precipitation seasons (mixed precipitation of the warm season). The latter breakdown of the mixed precipitation into seasons was applied in the section investigating their dependence on regional atmospheric circulation.

## Trends in the characteristics of the precipitation forms

### Liquid precipitation

All statistically significant trends of the characteristics of liquid precipitation were positive. The strongest and the most stable was the growth of the contribution of liquid precipitation to overall precipitation in September (at ca. +25% per decade), as documented by both tests of statistical significance in nearly all of the sub-periods (Table 3). In September, the frequency and totals of liquid precipitation were also growing significantly, but the trends were only clearly visible in the sub-periods between 1979–2000 and 1979–2004. Significant increase in the frequency and total of liquid precipitation was also observed in July in 1979–2004 to 1979–2007. The totals were growing on average by 29% per decade, while the growth rate of the number of days was much lower at not more than 19.4% and in most cases was confirmed by just one of the significance tests (Tables 1, 2). During recent years, i.e. in the periods from 1979–2006 onwards, a significant growth was observed in the frequency of liquid precipitation in June (by ca. 18% per decade).

### Mixed precipitation

There was a strict seasonality in the statistically significant trends of mixed precipitation (Tables 1–3). In some months of the cool season (November, December and January), the frequency, totals and contribution of mixed precipitation to the overall precipitation totals were increasing, while in the warm season months (June and September) the trends were reversed. The greatest change in mixed precipitation was observed in November and December. This is when the increase in the totals of mixed precipitation was particularly stable and reached on average 40% per decade in November and

Table 1. Relative trends (%, change per decade) in the number of days with liquid, mixed and solid precipitation. Trends are expressed as a percentage of the average from 1979–2009

| Period | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Season |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Liquid precipitation | | | | | | | | | | | | | |
| 1979–2000 | - | - | - | - | - | +2.4 | **+19.1†** | -0.5 | **+28.7*†** | - | - | - | +11.2 |
| 1979–2001 | - | - | - | - | - | +3.6 | **+19.4†** | -2.6 | **+29.6*†** | - | - | - | +11.2 |
| 1979–2002 | - | - | - | - | - | +1.0 | **+16.4†** | -1.3 | **+23.9*†** | - | - | - | +12.7 |
| 1979–2003 | - | - | - | - | - | +8.7 | +15.0 | -4.0 | +21.2 | - | - | - | +10.2 |
| 1979–2004 | - | - | - | - | - | +9.6 | **+17.0*†** | -2.2 | **+18.0*†** | - | - | - | +10.9 |
| 1979–2005 | - | - | - | - | - | +13.7 | **+15.5†** | +0.7 | +13.6 | - | - | - | +11.3 |
| 1979–2006 | - | - | - | - | - | **+17.8*†** | **+14.6†** | +3.0 | +11.6 | - | - | - | +13.5 |
| 1979–2007 | - | - | - | - | - | **+19.4*†** | **+12.9†** | +0.4 | +7.7 | - | - | - | +11.5 |
| 1979–2008 | - | - | - | - | - | **+18.4*†** | **+10.7†** | -0.9 | +11.8 | - | - | - | +10.5 |
| 1979–2009 | - | - | - | - | - | **+18.1*†** | +7.7 | -1.7 | +8.3 | - | - | - | +9.6 |
| Mixed precipitation | | | | | | | | | | | | | |
| 1979–2000 | +25.3 | **-55.3*** | -11.6 | **-23.9*** | +0.4 | -20.6 | - | - | -25.8* | -1.7 | +29.6 | **+42.3*†** | -3.0 |
| 1979–2001 | +22.1 | -41.4 | -21.7 | -17.8 | -3.7 | **-27.2*** | - | - | **-27.3*** | +1.2 | +25.4 | **+61.3*†** | -3.6 |
| 1979–2002 | +19.5 | **-46.6*** | -29.3 | -1.7 | -13.1 | **-34.6*** | - | - | **-30.3*** | -3.9 | +24.9 | **+56.5*†** | -7.7 |
| 1979–2003 | +9.3 | -30.1 | -30.4 | +26.4 | -14.5 | -37.7 | - | - | -34.3 | +3.4 | +27.0 | +45.4 | -7.5 |
| 1979–2004 | +12.2 | -35.5 | -18.1 | +29.1 | -12.7 | **-35.6*** | - | - | **-31.8*** | -1.3 | +15.9 | **+33.1*** | -8.5 |
| 1979–2005 | +11.0 | -26.6 | -12.2 | +22.0 | -13.8 | **-33.6*** | - | - | **-29.5*** | -5.1 | +20.9 | **+40.8*†** | -7.3 |
| 1979–2006 | **+38.6†** | -23.2 | -18.5 | +20.4 | -16.8 | -31.8* | - | - | **-29.1*** | -8.0 | **+26.9*†** | **+41.2*†** | -5.7 |
| 1979–2007 | **+33.9†** | -27.9 | -6.2 | +18.9 | -17.0 | **-28.5*** | - | - | **-21.3*** | +1.4 | **+29.5*†** | **+38.6*†** | -1.7 |
| 1979–2008 | +29.9 | -20.9 | -12.2 | +10.3 | -8.9 | **-20.8*** | - | - | **-18.8*** | -0.3 | **+22.1*†** | **+50.8*** | +0.3 |
| 1979–2009 | **+31.6*†** | -18.4 | -11.1 | +6.6 | +7.2 | -15.9 | - | - | **-15.5*** | +4.1 | **+22.9*†** | **+49.1*†** | +4.2 |
| Solid precipitation | | | | | | | | | | | | | |
| 1979–2000 | +7.0 | +0.5 | +16.2 | -0.2 | **+10.4*** | - | - | - | - | **+10.9*** | **+8.0*** | +6.8 | **+5.6†** |
| 1979–2001 | **+8.7*†** | +0.1 | +11.0 | +1.8 | **+11.3*** | - | - | - | - | +7.3 | **+5.6*** | +0.6 | **+4.0†** |
| 1979–2002 | **+7.9*†** | -1.3 | +5.7 | +2.8 | +6.1 | - | - | - | - | +3.3 | **+5.5*** | -0.2 | +2.1 |
| 1979–2003 | +4.7 | -0.3 | +5.3 | -1.7 | +5.0 | - | - | - | - | +4.6 | +5.4 | -0.8 | +2.0 |
| 1979–2004 | +2.2 | -2.9 | +7.8 | -1.0 | +6.3 | - | - | - | - | +4.0 | +4.7 | +5.0 | +2.7 |
| 1979–2005 | +1.4 | -2.7 | +3.8 | +0.6 | **+7.8*** | - | - | - | - | +5.9 | **+6.0*** | +5.6 | +2.9 |
| 1979–2006 | -1.1 | -2.5 | +0.2 | +3.7 | +4.7 | - | - | - | - | **+7.8*** | +4.0 | +5.1 | +1.7 |
| 1979–2007 | -0.6 | -3.1 | -0.3 | +3.2 | +4.3 | - | - | - | - | +5.6 | +4.3 | +3.9 | +0.9 |
| 1979–2008 | -0.3 | -2.5 | -1.9 | +1.9 | +3.2 | - | - | - | - | **+7.2*** | **+6.1*†** | +2.6 | +0.6 |
| 1979–2009 | -0.3 | -1.2 | +1.7 | -0.6 | -0.5 | - | - | - | - | **+6.4*** | **+5.0*** | +3.2 | +0.4 |

a) * statistical significance indicated by Mann-Kendal test (bold)  
b) † statistical significance indicated by *t* test (bold)  
c) – trends were not calculated

Table 2. Relative trends (%, change per decade) in liquid, mixed and solid precipitation totals. Trends are expressed as a percentage of the average from 1979–2009

| Period | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Season |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Liquid precipitation | | | | | | | | | | | | | |
| 1979–2000 | - | - | - | - | - | -7.6 | +26.1 | +26.4 | **+56.5*†** | - | - | - | +35.5 |
| 1979–2001 | - | - | - | - | - | -14.2 | +16.9 | +15.1 | **+60.0*†** | - | - | - | +28.9 |
| 1979–2002 | - | - | - | - | - | -6.9 | +14.6 | +20.9 | **+45.0*†** | - | - | - | +29.4 |
| 1979–2003 | - | - | - | - | - | -9.8 | +22.5 | +15.3 | **+43.2*†** | - | - | - | +26.9 |
| 1979–2004 | - | - | - | - | - | -14.7 | **+29.7*†** | +21.1 | **+38.7*†** | - | - | - | +30.0 |
| 1979–2005 | - | - | - | - | - | -16.9 | **+33.2*†** | +20.6 | **+31.7*** | - | - | - | +28.7 |
| 1979–2006 | - | - | - | - | - | +0.6 | **+29.6*†** | +16.9 | **+26.5*** | - | - | - | +28.6 |
| 1979–2007 | - | - | - | - | - | -2.7 | **+22.3*†** | +10.0 | +20.6 | - | - | - | +21.5 |
| 1979–2008 | - | - | - | - | - | -5.3 | +17.7 | +9.0 | **+28.4†** | - | - | - | +20.8 |
| 1979–2009 | - | - | - | - | - | -1.5 | +12.1 | +3.0 | +20.6 | - | - | - | +17.8 |
| Mixed precipitation | | | | | | | | | | | | | |
| 1979–2000 | +36.5 | **-53.7*** | -10.9 | -16.4 | +18.9 | +13.2 | - | - | +1.2 | -6.0 | **+72.9*†** | **+87.5*†** | **+20.4*†** |
| 1979–2001 | +23.1 | **-55.9*** | -20.0 | -17.1 | +20.0 | -1.3 | - | - | +7.0 | -8.1 | **+65.6*†** | **+82.6*†** | **+15.5†** |
| 1979–2002 | +19.8 | **-57.7*** | -26.9 | +6.9 | +5.6 | -12.9 | - | - | -1.6 | -9.7 | **+52.6*†** | **+68.4*†** | +8.7 |
| 1979–2003 | +9.5 | **-27.6*** | -31.3 | +12.8 | +0.2 | -21.7 | - | - | -10.4 | -8.8 | **+56.2*†** | **+65.9*†** | +7.3 |
| 1979–2004 | +6.1 | **-32.3*** | -5.2 | +27.0 | -5.8 | **-28.5*** | - | - | -12.9 | -3.7 | **+41.7*†** | **+50.5*†** | +6.9 |
| 1979–2005 | +7.6 | -12.6 | +7.7 | +18.0 | -6.7 | **-33.1*** | - | - | -15.0 | -0.6 | **+39.9*†** | **+51.8*†** | +8.1 |
| 1979–2006 | **+48.2†** | -13.1 | -0.6 | +11.9 | -13.5 | -32.7* | - | - | **-20.3*** | -2.7 | **+44.6*†** | **+50.4*†** | +9.3 |
| 1979–2007 | +40.8 | -18.3 | +11.2 | +11.5 | -19.0 | **-26.4*** | - | - | -2.0 | +14.0 | **+44.7*†** | **+48.8*†** | **+15.4*†** |
| 1979–2008 | +33.0 | +1.0 | +3.5 | +3.7 | -21.3 | **-24.8*** | - | - | +4.0 | +7.9 | **+37.1*†** | **+50.4*†** | **+13.6*†** |
| 1979–2009 | +33.1 | +6.8 | +3.8 | +8.1 | -19.3 | -19.9 | - | - | +17.5 | **+25.8†** | **+31.0*†** | **+41.5*†** | **+17.5*†** |
| Solid precipitation | | | | | | | | | | | | | |
| 1979–2000 | +14.5 | **-59.6*** | -9.6 | -40.6 | -4.8 | - | - | - | - | -10.0 | -5.5 | -12.6 | -16.6 |
| 1979–2001 | **+14.6*** | **-60.4*** | -15.2 | -37.5 | +9.1 | - | - | - | - | -12.2 | +4.7 | -12.6 | -14.6 |
| 1979–2002 | +10.4 | **-59.4*** | -18.3 | -27.9 | -2.9 | - | - | - | - | **-20.9*** | +9.5 | -11.4 | -15.3 |
| 1979–2003 | +3.0 | **-57.4*** | -14.0 | -30.3 | -3.8 | - | - | - | - | **-20.7*** | +1.8 | -14.4 | -16.7 |
| 1979–2004 | +2.6 | **-55.5*** | -8.8 | -33.9 | -7.8 | - | - | - | - | -18.8 | +0.3 | -2.5 | -15.0 |
| 1979–2005 | -1.4 | **-51.5*** | -8.5 | -35.6 | -6.2 | - | - | - | - | **-20.0*** | +2.9 | -2.7 | -15.0 |
| 1979–2006 | -3.1 | **-49.0*** | -9.6 | **-35.8*** | -11.5 | - | - | - | - | -13.1 | +0.7 | +1.2 | **-14.3*** |
| 1979–2007 | -3.0 | **-41.3*** | -13.5 | **-36.0*** | -10.0 | - | - | - | - | -6.2 | -1.9 | -1.4 | **-13.9*** |
| 1979–2008 | -4.2 | **-36.9*** | **-18.1*** | **-30.5*** | -3.5 | - | - | - | - | -7.5 | -3.4 | -2.8 | **-13.8*** |
| 1979–2009 | -6.6 | **-36.7*** | **-17.1*** | **-30.5*** | -8.1 | - | - | - | - | -10.0 | -4.3 | +0.9 | **-14.4*** |

a) * statistical significance indicated by Mann-Kendal test (bold)
b) † statistical significance indicated by *t* test (bold)
c) – trends were not calculated

Table 3. Relative trends (%, change per decade) in the contribution of liquid, mixed and solid precipitation to overall precipitation total. Trends are expressed as a percentage of the average from 1979–2009

| Period | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Season |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Liquid precipitation | | | | | | | | | | | | | |
| 1979–2000 | - | - | - | - | - | -16.5 | **-1.8*** | -1.0 | **+29.7*†** | - | - | - | +19.3 |
| 1979–2001 | - | - | - | - | - | -7.5 | -0.9 | -0.3 | **+28.3*†** | - | - | - | +16.6 |
| 1979–2002 | - | - | - | - | - | +2.0 | -0.3 | +0.2 | **+24.8*†** | - | - | - | +20.0 |
| 1979–2003 | - | - | - | - | - | +3.7 | -0.1 | +0.7 | +27.5 | - | - | - | +19.8 |
| 1979–2004 | - | - | - | - | - | +3.8 | +0.3 | -0.8 | **+27.6*†** | - | - | - | +20.8 |
| 1979–2005 | - | - | - | - | - | +7.9 | +0.7 | -0.3 | **+25.9*†** | - | - | - | +19.8 |
| 1979–2006 | - | - | - | - | - | +11.1 | +0.9 | +0.1 | **+27.0*†** | - | - | - | +19.2 |
| 1979–2007 | - | - | - | - | - | +8.0 | +1.2 | -4.3 | **+20.8*†** | - | - | - | +13.2 |
| 1979–2008 | - | - | - | - | - | +6.9 | +1.1 | -3.8 | **+20.6*†** | - | - | - | +13.4 |
| 1979–2009 | - | - | - | - | - | +7.4 | +0.9 | -6.4 | **+13.7*†** | - | - | - | +10.9 |
| Mixed precipitation | | | | | | | | | | | | | |
| 1979–2000 | -0.9 | -32.4 | +6.5 | -0.1 | +18.7 | +23.5 | - | | -29.2 | +5.4 | **+45.7*†** | **+69.3*†** | +5.7 |
| 1979–2001 | -9.7 | -35.1 | -5.5 | +0.1 | +15.1 | +10.0 | - | | -30.2 | +5.3 | **+40.5*†** | **+70.5*†** | +3.7 |
| 1979–2002 | -4.3 | **-39.7*** | -14.7 | +9.0 | +1.9 | -2.7 | - | | -29.6 | +0.4 | **+31.2†** | **+57.2*†** | -1.7 |
| 1979–2003 | -12.7 | -10.1 | -20.5 | +15.0 | +1.4 | -12.3 | - | | -35.9 | +5.2 | +38.2 | +64.0 | -1.5 |
| 1979–2004 | -11.4 | -17.1 | -6.2 | +14.3 | +1.7 | -20.0 | - | | **-36.4*** | +3.6 | **+25.7†** | **+49.2*†** | -3.2 |
| 1979–2005 | -1.8 | -7.1 | +1.5 | +12.9 | +0.8 | **-23.9*** | - | | **-35.2*** | +5.1 | **+25.6*†** | **+52.3*†** | -2.2 |
| 1979–2006 | +9.0 | -2.1 | -6.0 | +8.6 | -7.0 | **-26.6*** | - | | **-39.0*** | +2.9 | **+28.5*†** | **+50.5*†** | -1.7 |
| 1979–2007 | +8.3 | -8.6 | +9.4 | +15.2 | -12.6 | -18.5 | - | | **-25.3*** | +6.6 | **+31.4*†** | **+52.4*†** | +5.3 |
| 1979–2008 | +4.9 | +4.7 | +1.8 | +7.1 | -15.1 | -14.1 | - | | **-24.8*** | +3.2 | **+29.3*†** | **+55.3*†** | +4.2 |
| 1979–2009 | +12.3 | +10.8 | +6.1 | +14.9 | -8.2 | -12.5 | - | | -10.1 | +9.9 | **+21.9*†** | **+45.8*†** | +7.8 |
| Solid precipitation | | | | | | | | | | | | | |
| 1979–2000 | -0.7 | **+10.6*** | +1.5 | +2.9 | -0.4 | - | - | | - | -4.3 | **-41.7*** | **-42.3*** | **-31.6*** |
| 1979–2001 | +2.9 | **+11.2*** | +5.9 | +3.3 | +1.9 | - | - | | - | -6.3 | **-36.0*** | **-41.8*** | **-26.0*** |
| 1979–2002 | +1.0 | **+12.4*†** | +9.2 | +0.2 | -8.6 | - | - | | - | -16.4 | **-30.5*** | **-42.8*** | **-25.1*** |
| 1979–2003 | +4.4 | +4.5 | +11.3 | -5.6 | -5.6 | - | - | | - | -15.2 | -34.7 | -42.8 | -25.1 |
| 1979–2004 | +4.0 | **+6.4*** | +5.8 | -13.2 | -3.9 | - | - | | - | -18.5 | **-23.8*** | **-33.2*** | **-24.8*** |
| 1979–2005 | +0.4 | 0.0 | +0.3 | -10.9 | -3.7 | - | - | | - | -21.4 | **-22.7*** | **-32.5*** | **-24.5*** |
| 1979–2006 | -6.1 | -1.0 | +3.3 | **-13.2*** | -10.1 | - | - | | - | -15.4 | **-25.2*** | **-29.9*** | **-24.2*** |
| 1979–2007 | -5.4 | 1.2 | -2.4 | **-13.7*** | -2.0 | - | - | | - | -16.4 | **-26.5*** | **-30.0*** | **-22.9*** |
| 1979–2008 | -7.0 | -2.0 | +0.6 | -9.0 | +2.5 | - | - | | - | -13.7 | **-24.1*** | **-30.1*** | **-22.1*** |
| 1979–2009 | **-9.2*** | -6.1 | -0.9 | **-10.6*** | -2.0 | - | - | | - | -17.4 | **-26.5*** | **-27.5*** | **-22.3*** |

a) * statistical significance indicated by Mann-Kendal test (bold)
b) † statistical significance indicated by *t* test (bold)
c) – trends were not calculated

60% per decade in December. The magnitude of these trends decreased as the length of the period studied increased. For example, the December increase in the precipitation total during the sub-period 1979–2000 was 87.5% on average per decade, but only 41.5% per decade in 1979–2009. A significant and relatively stable change was also observed in the contribution of mixed precipitation to the overall precipitation total in both December and November, but the magnitude of this trend was weaker (at ca. +56% and +32% per decade, in terms of the average of trends for sub-periods with significant changes). From 2006 onwards, the number of days with mixed precipitation was growing significantly in November (by 25% per decade). In January, statistically significant trends were sporadic. In June and September during most of the sub-periods, there was a fall in the number of days with mixed precipitation, while in the sub-periods between 1979–2004 and 1979–2008 the mixed precipitation totals were falling (in June) as was their contribution to the overall precipitation totals (in September) (Tables 1–3). Only one of the tests confirmed the statistical significance of the June and September trends in the mixed precipitation characteristics.

### Solid precipitation

In a clear majority of the sub-periods, only one of the tests confirmed that solid precipitation trends were statistically significant and this was mostly the Mann-Kendall test. Of all the characteristics of solid precipitation, the most stable change was displayed by their contribution to the overall seasonal precipitation totals (down by 25% per decade on average) and to the overall precipitation in November (down by 29% per decade on average) and December (down by 34% per decade on average). This rate of decrease gradually waned in subsequent sub-periods (e.g. from 41.7% per decade in 1979–2000 to 26.5% per decade in 1979–2009 in November). Stable decreasing trends were also present in the long-term course of solid precipitation totals in February at 50% per decade. The maximum drop in the total solid precipitation in February was observed in 1979–2001 (at 60.4% per decade). In recent years, significant negative trends in the solid precipitation totals were also observed in March, April and in the whole of their season of occurrence (Table 2).

The direction of significant trends in the characteristics of precipitation types is consistent with temperature trends. Marsz (2007) found a significant growth in both annual (+1.0$^{O}$C/decade) and seasonal temperatures at Hornsund (winter: +1.3$^{O}$C/decade, spring: +0.6$^{O}$C/decade, summer: +0.3$^{O}$C/decade, autumn: +0.9$^{O}$C/decade). The winter temperature showing the strongest increase mainly caused by significant changes in December (+2.4$^{O}$C/decade) and November (+1.8$^{O}$C/decade) was significantly correlated with the frequency of mixed precipitation (Łupikasza 2008). These monthly temperature trends might, to some degree, be responsible for the significant change in the mixed precipitation characteristics. Increasing trends in the characteristics of liquid precipitation in September and July, as well as a decrease in the frequency of solid precipitation in February, might also result from positive temperature trends which, however, are not significant for these months. Therefore, it may be assumed that changes of both solid and liquid precipitation are more linked to atmospheric circulation or other precipitation-forming factors. This is proven by the results of previous research (Łupikasza 2008) showing a significant correlation between the seasonal frequency of liquid and solid precipitation and temperature only in autumn and summer, respectively. On the other hand, the temporal course of mixed precipitation is significantly linked to changes of temperature in almost all seasons except for spring (Łupikasza 2008).

At Hornsund significant trends (1979–2009) in the characteristics of overall precipitation were also observed in November (total: +9.2 mm/decade, frequency: +2.2 days/decade) and December (total: +6.9 mm/decade, frequency: +2.1 days/decade). Significant increase in the number of days with precipitation regardless of its type was also found in October (+1.6 days/decade). Trends in overall precipitation characteristics for other months were statistically insignificant.

## Relationships between macro-scale circulation (AO) and precipitation forms

### Long-term variability of AO and precipitation forms

The macro-scale atmospheric circulation described with the AO index was found to exert a weak influence on the course of the characteristics of all precipitation forms at Hornsund. Only the September variability of the number of days with liquid precipitation has a significant correlation (at $\alpha \leq 0.05$) with the AO. The relationship is negative, which means that as AO increases there are fewer days with liquid precipitation at Hornsund. Additionally, strong positive relationships, but limited only to the Pearson's correlation,

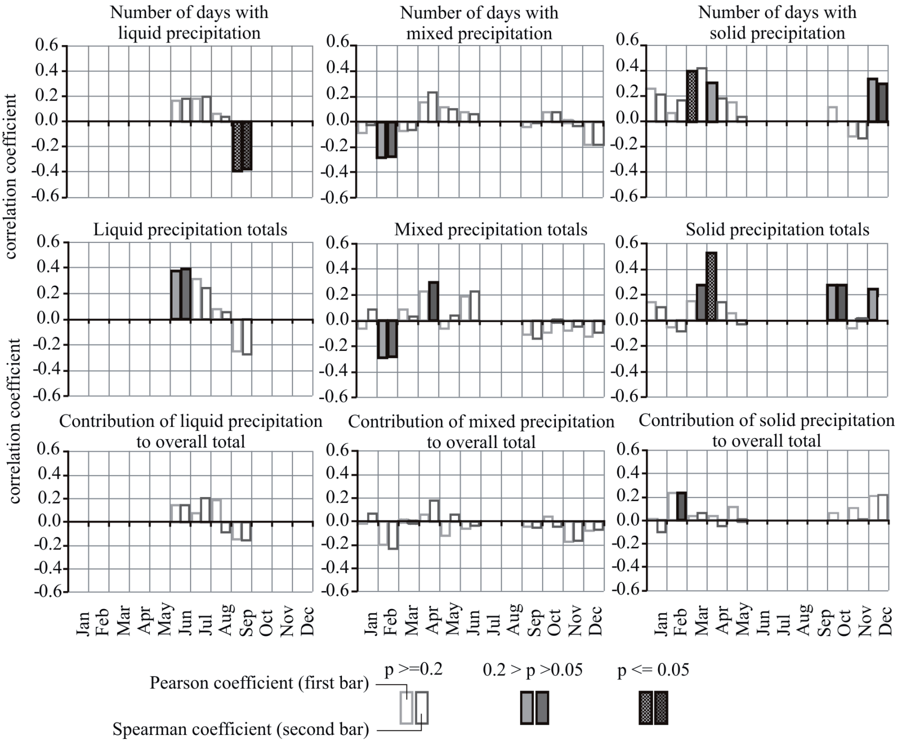


Fig. 2. Correlation coefficients between characteristics of liquid, mixed and solid precipitation and AO Index at Hornsund in the period 1979–2009 (*p – statistical significance level)*

were observed in March (number of days with solid precipitation) and in April (solid precipitation total). In certain months, the variabilities of days with precipitation and their totals displayed a weakly significant correlation with AO ($0.05<\alpha\leq0.2$). These relationships were observed in the case of the number of days and totals of mixed precipitation in February, the number of days with solid precipitation in December, totals of solid precipitation in October and liquid precipitation totals in June (Fig. 2). These correlations are positive with the exception of mixed precipitation in February.

## AO phase and precipitation forms

Based on an experimentally selected threshold value, three phases of the AO index were defined: positive (AO ≥ +0.5), neutral (+0.5 > AO > -0.5) and negative (AO ≤ -0.5). The threshold value was selected in a procedure that involved an inspection of the annual course of AO phases selected using three arbitrarily adopted threshold values of 0.2, 0.3 and 0.5, selected by looking at the statistical frequency distribution of the AO index. A correctly selected AO threshold value was defined as a value that should reflect the seasonal variability of circulation over Spitsbergen and this should be expressed by a clear differentiation of the AO phase frequency on an annual basis. The assumption used is clearly best met by adopting the AO threshold value of 0.5 (or +0.5 and -0.5) (Fig. 3).

Figure 4 shows the average numbers of days, totals and contribution of the various precipitation forms to the overall precipitation totals during the positive, neutral and negative AO phase. The average values of precipitation forms characteristics were expressed as a percentage of the long-term average (1979–2009) in this way eliminating an influence of the annual cycle on the comparability of the results. In general, no clear dependencies were found between the AO phase and the average values of the characteristics. Only the liquid precipitation total displays a clear differentiation of its average values depending on the AO phase. In the neutral phase, it was close to the long-term average. At the beginning of the liquid precipitation season, the total of this precipitation form was nearly one and a half times the long-term average (140%). During subsequent months, this proportion fell consistently to only 60% of the average in September. During the negative phase the dependencies are reversed: the liquid precipitation total in June is much lower than the average (at approximately 50%), but it gradually increases to reach more than 130% of the long-term average in September. The average values of the other characteristics are either weakly differenti-

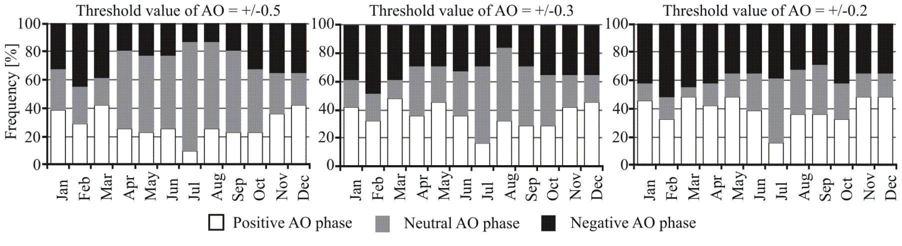


Fig. 3. Inter-annual variability in the frequency of AO phases for various threshold values

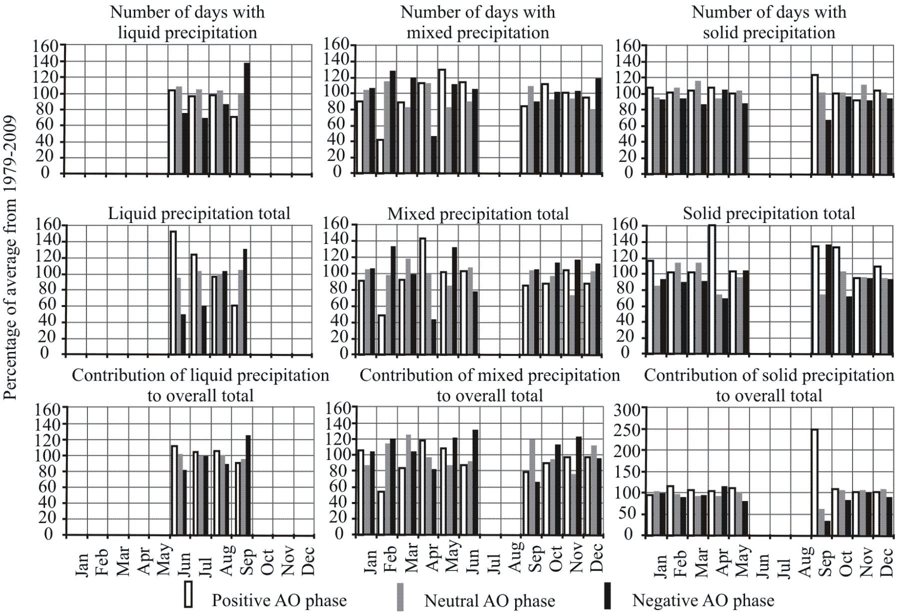


Fig. 4. Average values of the precipitation form characteristics for AO phases. The average values are expressed as a percentage of average (1979–2009) monthly values of particular characteristics with no regards to AO phases from the period

ated by the AO phase (e.g. the number of days with solid precipitation and the contribution of the solid precipitation to the overall total shown in Fig. 4) or their differentiation changes from month to month (e.g. the characteristics of the mixed precipitation shown in Fig. 4).

## Relationships between regional circulation and precipitation forms

Two of the characteristics, i.e. the number of days and totals, were used to identify the influence of the regional atmospheric circulation on the precipitation form. The first part of this section discusses the average daily totals (calculated from days with precipitation, including trace one) of all three forms of precipitation and their probability of occurrence in each circulation type (conditional probability). The section then covers circulation types that have a significant influence on the long-term variability of the number of days and of the seasonal totals of all three precipitation forms.

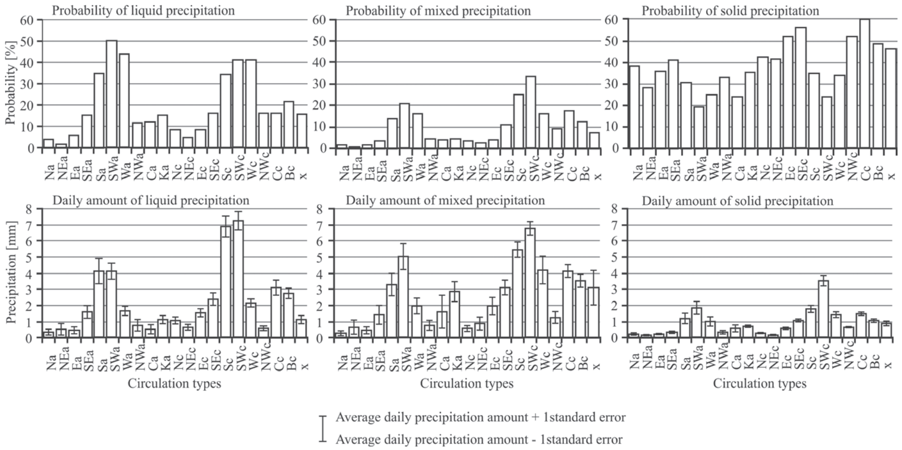


Fig. 5. Probability and daily amount of precipitation forms in circulation types in the period 1979–2009

### The occurrence and amount of precipitation in different circulation types

At Hornsund, the greatest probability of snowfall is associated with a centre of low pressure (ca. 60%). Solid precipitation is also highly likely (at more than 50%) during days with the types SEc, Ec and NWc (Fig. 5). Mixed precipitation is mostly favoured by SWc and SWa, both in terms of occurrence and the highest daily totals. The highest probability of liquid precipitation is recorded, surprisingly, during the influence of anticyclonic types with south-western air flow (50%) and western air flow (43.7%). These types (SWa and Wa), however, favour the occurrence of trace precipitation and hence the highest totals are favoured by a non-overlapping set of types, i.e. SWc and Sc. The south-western and southern air flows also favour the occurrence of mixed precipitation when Spitsbergen is influenced by a low pressure centre (ca. 40%).

The highest daily totals of all three precipitation forms are recorded during southwestern advection when the archipelago is under the influence of a low pressure system (SEc type, liquid: 7.2 mm, mixed: 6.8 mm, solid: 3.5 mm). Southern air flow is also associated with relatively high precipitation coinciding with high pressure systems (respectively: 4.1 mm, 5.0 mm and 1.8 mm) (Fig. 5). High totals of liquid precipitation are also generated by the Sc (6.9 mm) and Sa (4.1 mm) types.

## Long term variability of precipitation characteristics and frequency of circulation types

In order to determine the influence of the regional circulation on the long-term variability of the precipitation types, correlation coefficients between seasonal frequency of the circulation types and seasonal values of the precipitation characteristics (totals and number of days) were calculated. As the relationships between precipitation and circulation at Hornsund are seasonal (Łupikasza and Niedźwiedź 2002) and mixed precipitation is recorded all year round, this form of precipitation was analysed separately in the liquid and solid precipitation seasons.

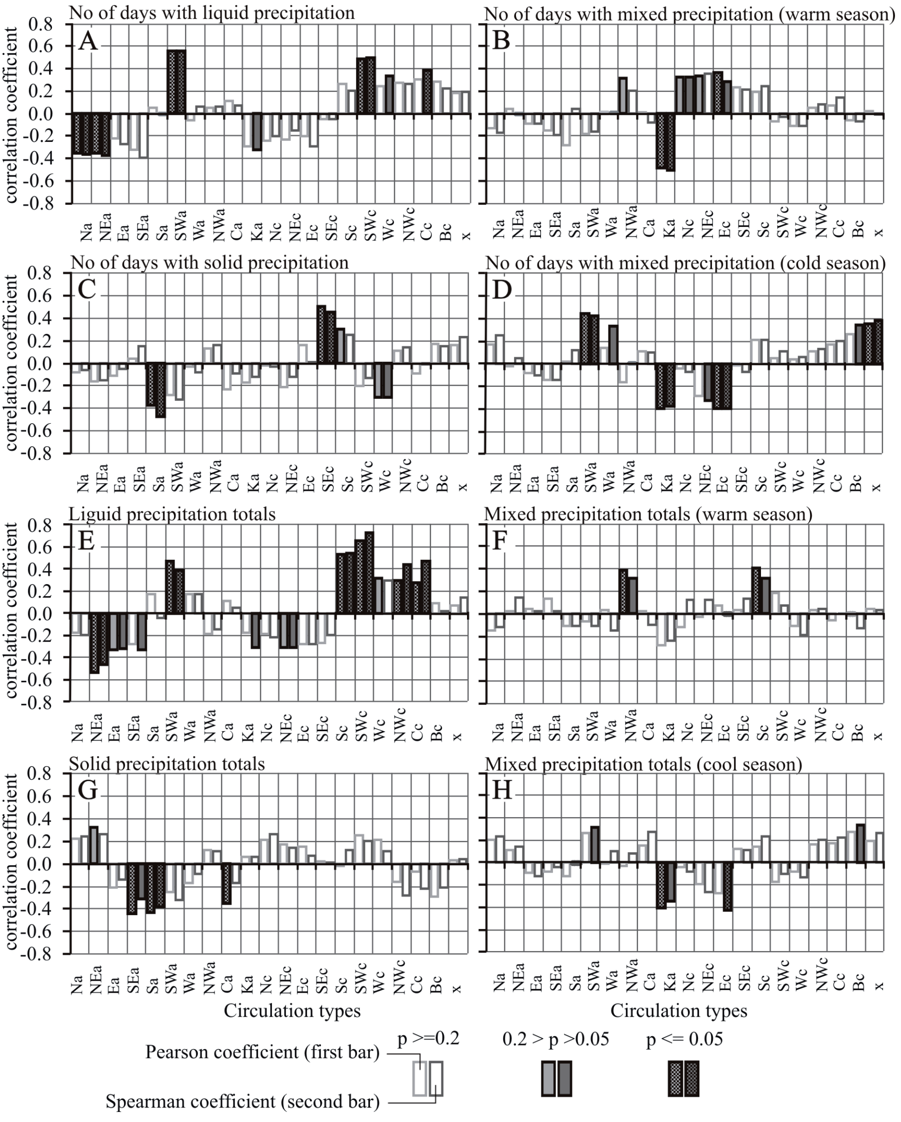
The greatest influence on the long-term occurrence and totals of liquid precipitation is exerted by the frequency of southwestern air flow (positive correlations), both at times of low and high pressure systems (SWc and SWa) (Fig. 6A, E). The temporal course of these types explains 53% (SWc) and 22% (SWa) of the variability in the liquid precipitation totals and 31% (SWa) and 25% (SWc) of the variability in the frequency of that precipitation type. A drop both in frequency and in rainfall totals is associated with the increasing frequency of the NEa type, which explains 14% and 28%, respectively, of the variability in the characteristics under discussion. Northeastern air flow significantly reduces the amount of rain even during a low (NEc), but the relationship is a weak one. The decrease in the number of days with rainfall is also a result of the higher frequency of the northern anticyclonic situation (Na), which explains 13% of the variability in the long-term course of this characteristic. The totals of liquid precipitation are also significantly positively correlated with the frequency of the types: Sc (coefficient of determination: 29%), Cc (23%) and NWc (19%). Daily temperature anomalies in synoptic types favouring the liquid precipitation occurrence are positive whereas they are negative in types lowering the characteristics of this precipitation type. However, it must be borne in mind that in summer the relationships between daily temperature and regional atmospheric circulation are the weakest (Niedźwiedź 2008).

Sa is the only type that determines the long-term variability of both the frequency and the totals of solid precipitation. Spitsbergen then receives warmer air masses in winter and a reverse correlation is produced. The variability in the temporal course of both frequency and totals of solid precipitation can be explained by the variability of the Sa situation in 22% and 19%, respectively. A significant decrease of snowfall totals is also associated with the frequency of south-eastern air masses under a high (SEa); in this case coefficient of determination reaches 20%. It is also worth noting that south-eastern winds during a low pressure system cause a clearly increased frequency of solid precipitation (coefficient of determination: 26%), but have no effect whatsoever on its totals (type SEc).

During both the warm and cool seasons, the regional circulation exerts a stronger influence on the long-term frequency of mixed precipitation than on its totals (Fig. 6B, D, F, H). During the cool season, the occurrence of mixed precipitation is favoured by the SWa type, which explains 20% of variability of this characteristic. The long-term course of the frequency of mixed precipitation is also significantly correlated with the unclassified type x with a coefficient of determination reaching 15%. The high-pressure ridge (Ka) and the Ec types have a reverse influence (negative correlation; coefficient of determination: 15% and 16%, respectively). Most of the circulation types mentioned above also determine the long-term variability of mixed precipitation totals during this season, only the strength of the dependencies is statistically lower. An exception is the Ka type which explains the 15% of variability in both totals and frequency of mixed precipitation in the cool season (Fig. 6H). The occurrence of days with mixed precipitation is also strongly negatively correlated with the Ka type during the warm season (coefficient of determination: 25%). It is interesting that the character of the relationships between the frequencies of mixed precipitation and some circulation types (Nc, NEc, Ec) changes depending on the season. In the warm season the occurrence of these types is connected with an inflow of cool air leading to an increase in the frequency of mixed precipitation. The effect is reversed in the cool season when an inflow of cooler air is unfavourable for the formation of mixed precipitation. The long-term change of mixed precipitation totals in the warm season is determined by the frequency of the NWa and Sc types (negative correlation). Both the types explain about 15% of the variability in this characteristic of mixed precipitation (Fig. 6F). Summer daily temperature anomalies in these types are positive (Niedźwiedź 2008).

## Conclusions

At Hornsund, the characteristics of the precipitation forms studied underwent changes in different directions depending on both precipitation form and on the period studied (month, season). The changes were most significant in the



No of days with liquid precipitation

No of days with mixed precipitation (warm season)

No of days with solid precipitation

No of days with mixed precipitation (cold season)

Liguid precipitation totals

Mixed precipitation totals (warm season)

Solid precipitation totals

Mixed precipitation totals (cool season)

Fig. 6. Correlation coefficients between precipitation form characteristics and frequency of circulation types in the period 1979–2009

case of liquid and mixed precipitation. Trends in liquid precipitation characteristics were mainly positive. The most significant and stable was the increase in totals and contribution of liquid precipitation to the overall total in September, whereas the frequency of rain has been growing significantly in July. Direction of trends in mixed precipitation varied depending on month. The strongest and stable was the increase in the totals of mixed precipitation in December (60% of the average per decade) and November (40%). The weakest, if stable, trends were observed in the frequency of solid precipitation. Snowfall totals have been significantly decreasing in February.

The macro-scale atmospheric circulation described herein with the AO index has a minor influence on the long-term course of precipitation in any of the forms. An exception is September when the Hornsund area records fewer days with liquid precipitation as the AO index value grows. No clear dependencies were identified between the AO phase and the average monthly values of the characteristics, with the exception of the number of days with liquid precipitation. At the beginning of the liquid precipitation season (in June) the frequency of rain during the positive AO phase is nearly one and a half times larger than the long-term average (140%). In subsequent months, it gradually drops to reach just above a half of the initial value (60%) in September. Reverse relations are observed during the negative phase. Thus, the NAO phase could to some degree account for the observed variability in the number of days with liquid precipitation.

The Hornsund area experiences a marked influence of the regional atmospheric circulation on the occurrence of liquid, mixed and solid precipitation. Both the highest frequency and the highest daily amounts of precipitation types studied are usually linked to air flow from the different directions of the southern sector. The south-west cyclonic situation generates the highest totals of all the precipitation forms. SW air flow is also conducive to high daily totals in anticyclonic conditions. The highest probability of both liquid and mixed precipitation is associated with air arriving from the southwest (and west in the case of rain), but liquid precipitation is more likely in anticyclonic situations (SWa, Wa), whilst mixed precipitation is more frequent under low pressure systems (SWc). The greatest probability of snowfall is associated with the centre of low (at approximately 60%).

Long-term variability of the precipitation form characteristics is significantly dependent on the frequency of some circulation types but relationships are rather complex. An inflow of air from the southern sector (warm air) favours the occurrence and totals of liquid precipitation in the warm season whereas it significantly decreases the values of solid precipitation characteristics and the frequency of mixed precipitation in winter. An inflow of cool air from the north-eastern sector in the warm season has a negative effect on the characteristics of liquid precipitation under the influence of an anticyclone whereas it increases the frequency of mixed precipitation under the influence of a cyclone. Such a direction of air inflow in the cool season is unfavourable to the occurrence of mixed precipitation. Long-term variability of mixed precipitation is poorly correlated with the frequency of the majority of circulation types.

The variability in the characteristics of precipitation types tends to be triggered more by the regional circulation (particularly the direction of the local advection) than by macro-scale circulation (AO).

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