# THE IMPACT OF CIRCULATION TYPES AND THEIR CHANGING THERMAL PROPERTIES ON THE PROBABILITY OF DAYS WITH SNOWFALL AND RAINFALL IN POLAND, 1966–2020

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Abstract: The frequency of snowfall and rainfall is expected to change due to the warming climate. However, trends in liquid and solid phases are not linearly related to air temperature trends. This paper discusses the impact of thermal properties of circulation types (CTs) on the trends in snowy and rainy days in Poland in the period 1966–2020. The visual observations from 42 synoptic stations, which constitute the most-reliable information on precipitation type, were used to identify the precipitation phase. In most CTs, the air temperature increased between 1966–1985 and 2001–2020, but at various rates depending on the type of circulation. Positive tendencies in the thermal properties of CTs contributed to decreasing trends in winter snowfall and increasing trends in winter rainfall. The rate of tendencies in the probability of the precipitation phases depended on the average temperature and the intensity of warming, in particular CTs. In winter, both the snowfall and rainfall tendencies were the strongest for those CTs with average air temperatures (ATs) close to the freezing point, particularly when the average had crossed that threshold between the years 1966–1985 and 2001–2020. The most rapid tendencies in winter snowfall and rainfall, and in the spring mixed phase were induced by N and NW air advection under cyclonic conditions, bringing air from the rapidly warming Arctic. No trends in the winter mixed precipitation probability resulted from its various tendencies in particular CTs. The probability of snowfall increased during air advection from the southeastern sector, particularly in winter.

Keywords: air temperature, atmospheric circulation, rain, snow, warming

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## Introduction

The snowfall frequency and amount and the snowfall-to-precipitation ratio are considered important indicators of climate change due to their sensitivity to air temperature in the lower troposphere (Kapnick, Delworth 2013, Viste, Sorteberg 2015, Deng et al. 2017, Sims, Liu 2017), which, according to the latest Intergovernmental Panel on Climate Change report, increased at a rate of 1.07°C (0.8–1.3°C) from 1852–1900 to 2010–2019 (IPCC 2021). Increasing trends in air temperature and the resulting changes in the precipitation phase structure have impacts on the hydrological and energy cycles (Mackay 1987, Loth et al. 1993, Stieglitz et al. 2003, Grab 2005) and may have serious environmental consequences. Solid precipitation, which is vital for snow cover development, plays important roles in the environment by modifying the radiation balance (increased albedo) and impacting large-scale climate dynamics (Barnett et al. 1989, Cohen, Entekhabi 2001,



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Gong et al. 2002, 2003a, b, 2004), stream flow and hydrological drought occurrences in spring and summer, snowmelt flooding (Feng, Hu 2007) and winter sports and recreation (e.g., Scott et al. 2008). Heavy snowfall can also be a serious risk to human life and property (Andersson, Gustafsson 1994, Garcia, Salvador 1994, Wild et al. 1996, Spreitzhofer 1999, Strasser 2008). Knowledge of the variability in precipitation phases, particularly snowfall, is important for hydrological modelling and water-resource management (Diodato, Bellocchi 2020).

In many parts of the world, a warming-induced decrease in solid precipitation has become common since the second half of the 20th century (Huntington et al. 2004, Knowles et al. 2006, Serquet et al. 2011, Marty, Blanchet 2012, Twardosz et al. 2012, Nikolova et al. 2013, Tamang et al. 2017, Hynčica, Huth 2019a, b). Although the occurrence of snowfall and rainfall is sensitive to air temperature trends, the relationships between these variables are not straightforward and depend on the average climate conditions (Davis et al. 1999, Knowles et al. 2006, Ye 2008, Krasting et al. 2013, Bintanja 2018). The shifts in the structure of precipitation phases are most significant when an average air temperature (AT) is close to the freezing point with regard to both locations and seasons (Knowles et al. 2006, Feng, Hu 2007, Łupikasza, Cielecka-Nowak 2020). In very cold conditions, strong warming may cause no shifts in precipitation phases or an increase in snowfall because air temperature remains well below freezing (Knowles et al. 2006). In a few countries in the Balkans, despite warming, extreme snowfall events are more frequent due to specific synoptic situations in which the stronger prevalence of Atlantic ridges or blocking patterns coexist with deeper cyclonic structures over the Adriatic and Tyrrhenian seas (Faranda 2020). Although air temperature can explain a large part of the variance in the frequency of snowfall and rainfall, atmospheric circulation also plays a significant role and complicates the straightforward relationships between global warming and precipitation phases. Many studies have confirmed the prominent role of atmospheric circulation in the occurrence of both extreme snowfall (e.g., Mote et al. 1997, Grundstein 2003, Farukh, Yamada 2014, Bednorz, Wibig 2016, 2017, Yang et al. 2019, Faranda 2020, D'Errico et al. 2022) and snow cover worldwide (e.g., Falarz 2007, Popova 2007, Wu, Kirtman 2007, Ye, Wu 2017, Baltaci et al. 2020).

Atmospheric circulation, more specifically the direction of air advection, determines the thermal properties of air masses inflowing from various directions over a region; therefore, it is an important driver of snowfall or rainfall occurrence. We assume that global warming must have increased the temperature of air masses; however, due to unevenly distributed warming rates and regional conditions, the increase in air temperature differs depending on the direction of advection (CT – circulation type). This effect was mentioned by Suriano and Leathers (2017), who studied circulation patterns conducive to lake-effect snowfall in the United States and stated that temperature changes do not necessarily manifest themselves equally across all synoptic-scale weather patterns. Thus, we hypothesise that synoptic types (various directions of air advection) can contribute differently to trends in precipitation phases. Merino et al. (2014) pointed out a need to study the behaviour of weather-pattern properties under global warming as a basis for future analysis of trends in snowfall, similar to other meteorological variables. Ohba and Suimoto (2020) demonstrated that in Japan, climate change will have a major impact on the relationships between synoptic weather patterns and heavy wet snowfall. Additionally, modelling studies indicate that only a small subset of the CTs that generate snowfall in the current climate will be able to do so in the future, as they will be significantly warmer (Cattiaux et al. 2012) and thus may produce rain instead of snowfall. Possible global warming-generated changes in the properties of CTs and Poland's location in a zone where continental and maritime air masses interact, influencing the structure and trends in precipitation phases, the rate of which is not parallel to the spatial pattern of seasonal air temperature trends, motivated us to study the impact of various CTs and changes in their thermal properties on the occurrence and tendencies in precipitation phases in Poland. We study the thermal properties of CTs based on sea level pressure because global warming manifests itself strongest in the lower troposphere.

This study aims to answer the following questions:

1. Which regional CTs, particularly the direction of air advection, determine the occurrence of particular precipitation phases the most?
2. Which CTs most contribute to current trends in precipitation phases due to changes in their thermal properties?

The impact of the changing thermal properties of CTs on the probability of solid, liquid and mixed precipitation has not yet been studied in Poland (and not to the knowledge of authors in other locations), nor have been the relationships between the CTs and precipitation phases.

## Data and methods

### Meteorological data and identification of precipitation phases

Due to a lack of data on precipitation type, the precipitation phase is frequently identified based on daily air temperature by adopting various thresholds to discriminate solid from liquid phases, usually varying between 0°C and 4°C (e.g., Deng et al. 2017, Irannezhad et al. 2017, Zhong et al. 2018, Hynčica, Huth 2019b). In this study, precipitation phases were identified based on standard visual observations of present (ww) and past weather (W1 W2) (3 h time resolution) at 42 synoptic stations in Poland in the period 1966–2020 (Fig. 1A). Snowfall occurs at wide air temperature ranges; thus, visual observations are the most reliable source of information on the precipitation phase.

At most stations (38 stations), the data were complete. The chronological series from four stations are shorter (Kozienice starts in 1977, Piła starts in 1971) or include gaps (Częstochowa – gaps between 1994 and 1997, Kraków – gaps between 2003 and 2012). Based on sub-daily identified precipitation phases, each day in the research period was classified as a day with a solid phase (hereafter Sd), liquid phase (hereafter Lq) or mixed phase (hereafter Mx). The days with the Mx phase include both days with sleet, sleet and Lq, sleet and Sd and days when Sd and Lq occurred during various parts of a day. Such an approach guaranteed the discrimination of days with only snowfall and days with only rainfall.

### Circulation types

Average daily sea level pressure from NCEP/NCAR reanalysis (Kalnay et al. 1996) was used to assess the impact of mesoscale atmospheric circulation on the precipitation phase. To assess the thermal properties of CTs, it was crucial to identify the direction of air advection for each

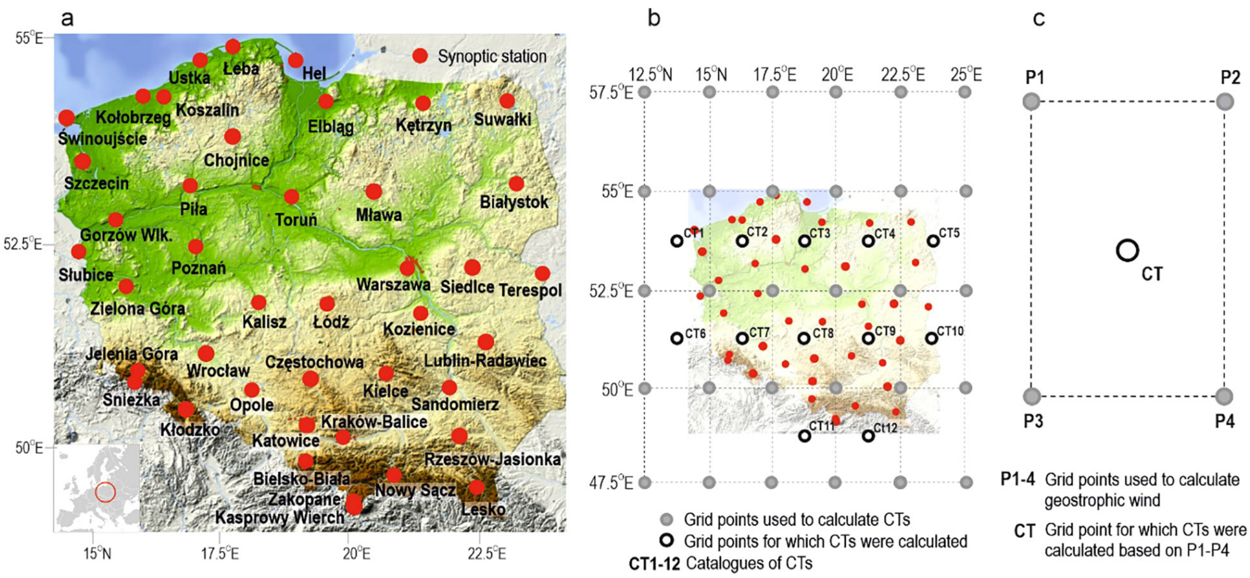


Fig. 1. Location of synoptic stations used in this study in Poland (A), and distribution of grids over Poland for which circulation types were identified (B), an example distribution of grids for calculating geostrophic wind used to identify a direction of air advection (C).

grid point located within the study area (black circles in Fig. 1B) and each day in the research period. Thus, 12 calendars of CTs (CT1–CT12 in Fig. 1B) were created. The regional approach, i.e. calculation of several CTs' catalogues was necessary because, during most days, various precipitation types usually occurred in different parts of Poland which, besides local conditions, were related to various directions of air advection and thus various thermal properties of inflowing air masses. The direction of air advection was identified based on the direction of the geostrophic wind calculated separately for grid points (CT1–CT12 in Fig. 1B) within the research area using the formula given by Holton and Hakim (2012); and based on the daily sea level pressure from the surrounding grid points (P1, P2, P3 and P4) as shown in Figure 1C. The commonly used thresholds of 1013 hPa and 2 m · s$^{-1}$ of geostrophic wind speed were adopted to identify the type of baric centre (>1013 – anticyclonic, ≤1013 – cyclonic) and non-advective CTs (geostrophic wind <2 m · s$^{-1}$). Of the 18 distinguished CTs, 16 types informed the direction of air advection (Table 1). Two non-advective thus unclassified types, Oc and Oa, constituted 2% of the cases. The impact of CTs and their thermal properties on the occurrence and variability in precipitation phases at each station was studied using the CTs calendar from the grid closest (smaller distance) to a particular synoptic station.

Table 1. Classification of circulation types.

| Anticyclonic types | Cyclonic types | Direction of air advection |
|---|---|---|
| Na | Nc | Northern |
| NEa | NEc | Northeastern |
| Ea | Ec | Eastern |
| Sea | Sec | Southeastern |
| Sa | Sa | Southern |
| SWa | SWc | Southwestern |
| Wa | Wc | Western |
| NWa | NWc | Northwestern |
| Oa | Oc | Non-advective types |

## Long-term variability and trends in the frequency of precipitation phases

All calculations were performed for seasons when various precipitation types occur in Poland, i.e. autumn (September, October, November [SON]), winter (December, January, February [DJF]) and spring (March, April, May [MAM]). Based on daily data, the chronological series of a seasonal number of days with Sd, Mx and Lq were calculated for each station. Based on the station series, the country series of the seasonal numbers of precipitation phases (hereafter country series) were calculated as arithmetical averages.

The trend slopes in the seasonal series of the precipitation phases frequency were calculated with Sen's method (Sen 1968). The statistical significance of trends was checked with Mann–Kendall modified for autocorrelation (Mann 1945, Kendall 1975, Hamed, Rao 1998) adopting the threshold of α ≤0.1 for weak trends and α ≤0.05 for significant trends.

## Relationships between precipitation phases and circulation types

To analyse the relationships between precipitation phases and atmospheric circulation, the conditional probability (CP), i.e. frequency of each precipitation phase under the condition of the occurrence of a given CT, was calculated for each station and each season according to Eq. (1).

$$CP = (N_{PCT} / N_{CT}) \times 100\% \tag{1}$$

where:
- $CP$ is a conditional probability,
- $N_{PCT}$ is the number of days with a particular precipitation phase during a particular CT,
- $N_{CT}$ is the number of days with a particular CT.

CP accounts for various frequencies of particular CTs and thus is a better probabilistic measure than frequency. Station CPs were then averaged to create the country patterns of seasonal CPs of precipitation phases in CTs. The CT was recognised as favourable (unfavourable) to the occurrence of a given phase if its probability in that CT was higher (lower) than the seasonal probability of phase ±1σ (standard deviation). The average probability was calculated as an arithmetical average from 18 values of CP for particular CTs.

To assess the thermal properties of CTs, the average AT was calculated for each CT for the entire research period (1966–2020) and two subperiods, 1966–1985 (cold period) and 2001–2020 (warm period). In the first period, 1966–1985, the air temperature was lower than in the latest period by 0.9–2.0°C in DJF and 0.6–2.1°C in MAM and SON depending on the station. Next, to assess the changes in the thermal properties of particular CTs, differences in air temperatures between 1966–1985 and 2001–2020 were also calculated for each CT and each station separately. We subtracted the first period from the second (2000–2020 − 1966–1985) so that positive (negative) changes correspond to an increase (decrease) in air temperature. Changes in precipitation phases depend not only on the air temperature trend but also on mean air temperature, particularly when changes in mean occur close to the freezing point. Therefore, in this study, we used the above-mentioned differences instead of trend analysis.

Long-term changes in precipitation phases depending on CTs were calculated as the differences in the CP of a particular precipitation phase between 1966–1985 and 2001–2020 (hereafter tendencies) for each CT. These tendencies were assumed to result from the various thermal properties of CTs and various rates of warming depending on CT. The thermal properties of CTs are understood in this paper as the average AT on days with a particular CT, i.e. the direction of air advection and the type of baric centre. The resulting differences in the probabilities of precipitation phases and air temperature for CTs between 1966–1985 and 2001–2020 are called tendencies to distinguish them from statistical trends calculated with the Mann–Kendall method.

## Results and discussion

### Long-term variability and trends in the frequency of precipitation phases

Long-term variability and trends in the seasonal number of days with precipitation phases are presented in Figure 2. Trend analysis showed a significant decrease in the mixed precipitation in transitional seasons and significant opposite trends in Sd (negative) and Lq (positive) in DJF on the country scale. Trends in Sd were also negative in MAM and SON; however, they were weakly significant. In all seasons, the frequency of Sd has been very low since 2011 or 2014, depending on the season (Fig. 2).

Corresponding trends in snowfall or snowfall-to-precipitation ratio have been reported in many parts of Europe since the second half of the 20th century (Førland, Hanssen-Bauer 2003, Łupikasza 2008, Serquet et al. 2011, Marty, Blanchet 2012, Twardosz et al. 2012, Nikolova et al. 2013, Hynčica, Huth 2019b, Łupikasza et al. 2019, Førland et al. 2020, Łupikasza, Cielecka-Nowak 2020).

Significant negative trends in Mx were more numerous in MAM than in SON, covering most stations in western Poland, which is more prone to maritime influences than in eastern Poland. Considering the Lq, a significant increase was found only in the frequency of winter rains (DJF), particularly at stations located in northern and southern Poland (Fig. 2). The country-averaged series indicated a rapid increase in winter rains since the beginning of the 21st century (Fig. 2). An increased frequency of winter rainfalls with serious environmental consequences was previously found in the Arctic, Russia and northern Eurasia (Pedersen et al. 2015, Vikhamar-Schuler et al. 2016).

Although the direction of trends in precipitation phases agreed with general warming, their spatial pattern was complicated and varied depending on index and season and did not follow the pattern of air temperature trends in Poland (not shown). Previous studies attributed the complicated and non-linear response of precipitation phases to warming to ambient temperature and average climate conditions (Davis et al. 1999, Knowles et al. 2006, Ye 2008, Krasting et al. 2013, Bintanja 2018). Since the rate of global warming varies regionally (IPCC 2021), the increase in air temperature in a given location may be influenced by the frequency and direction of air advection, thus influencing the precipitation phases. Therefore, a further part of this study focuses on the relationships between the occurrence of precipitation phases and CTs.

### Conditional probability of precipitation phases depending on regional circulation types

The box plots in Figure 3 show the statistical distribution of station probabilities of precipitation phases for particular CTs from a seasonal perspective in Poland. Maps in Figure 4 show

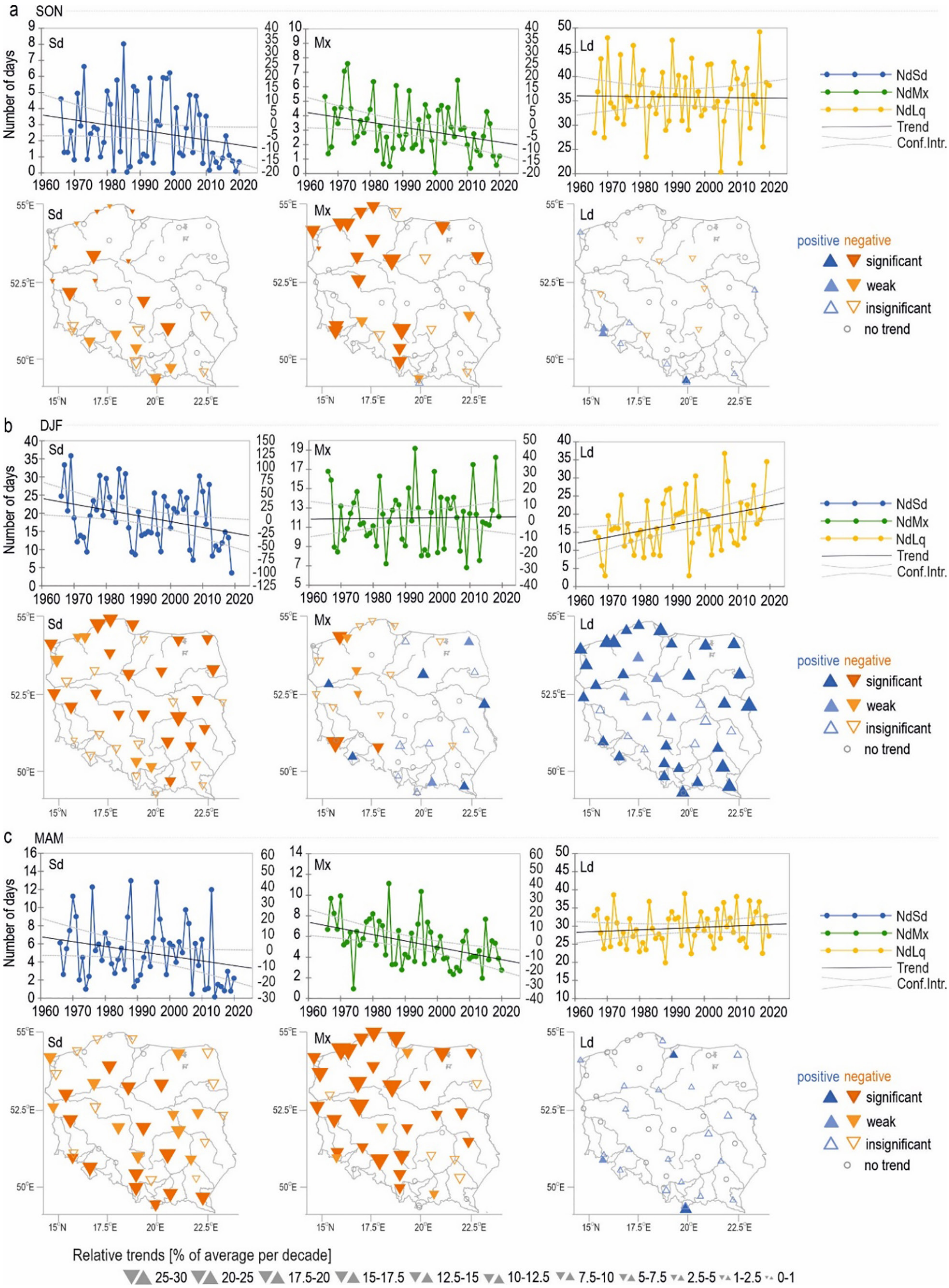


Fig. 2. Long-term variability in the number of days with precipitation phases averaged over stations (graphs) and spatial distribution of trends (maps) in the number of days with precipitation phases (Sd, solid; Mx, mixed; Lq, liquid, yellow) in the period 1966–2020.

spatial patterns of the Sd, Mx and Lq probabilities for advective cyclonic CTs in DJF when solid and mixed phases are the most frequent.

The CP (hereafter probability) of precipitation phases in particular CTs varied seasonally; however, the pattern of the relationships remained similar year-round. Different probabilities of phases in CTs resulted from various thermal properties of air inflowing over Poland from various directions (discussed in Section 3c). The probability of all precipitation phases in cyclonic CTs being more favourable for convection was larger than in corresponding anticyclonic types. Snowfall was most likely during air advection from the NE–E sector and NW under the influence of a cyclone (Fig. 3), particularly at southern stations located in hilly and mountainous areas (Fig. 4) due to a colder climate and amplified orographically forced convection (Łupikasza 2016). The NEc type was also particularly conducive to snowfall at the most northwestern stations located at the Baltic Sea shore (Fig. 4). The NE advection of cold air masses over the warmer sea surface enhances convection and is conducive to the so-called sea-effect snowfall at the Polish shore of the Baltic Sea (Bednorz et al. 2022). In DJF, the probability of snowfall on days with the NEc type exceeded 51% at more than 50% of the stations. In DJF, the NEc and Ec were the coldest cyclonic types, with average AT below −4°C ranging from −0.9°C to −12°C at particular stations. The NWc type was warmer; however, the average AT was still below the freezing point (−0.8°C).

The northeastern advection (Ec and NEc) also favoured the solid phase in SON (Fig. 3). In that

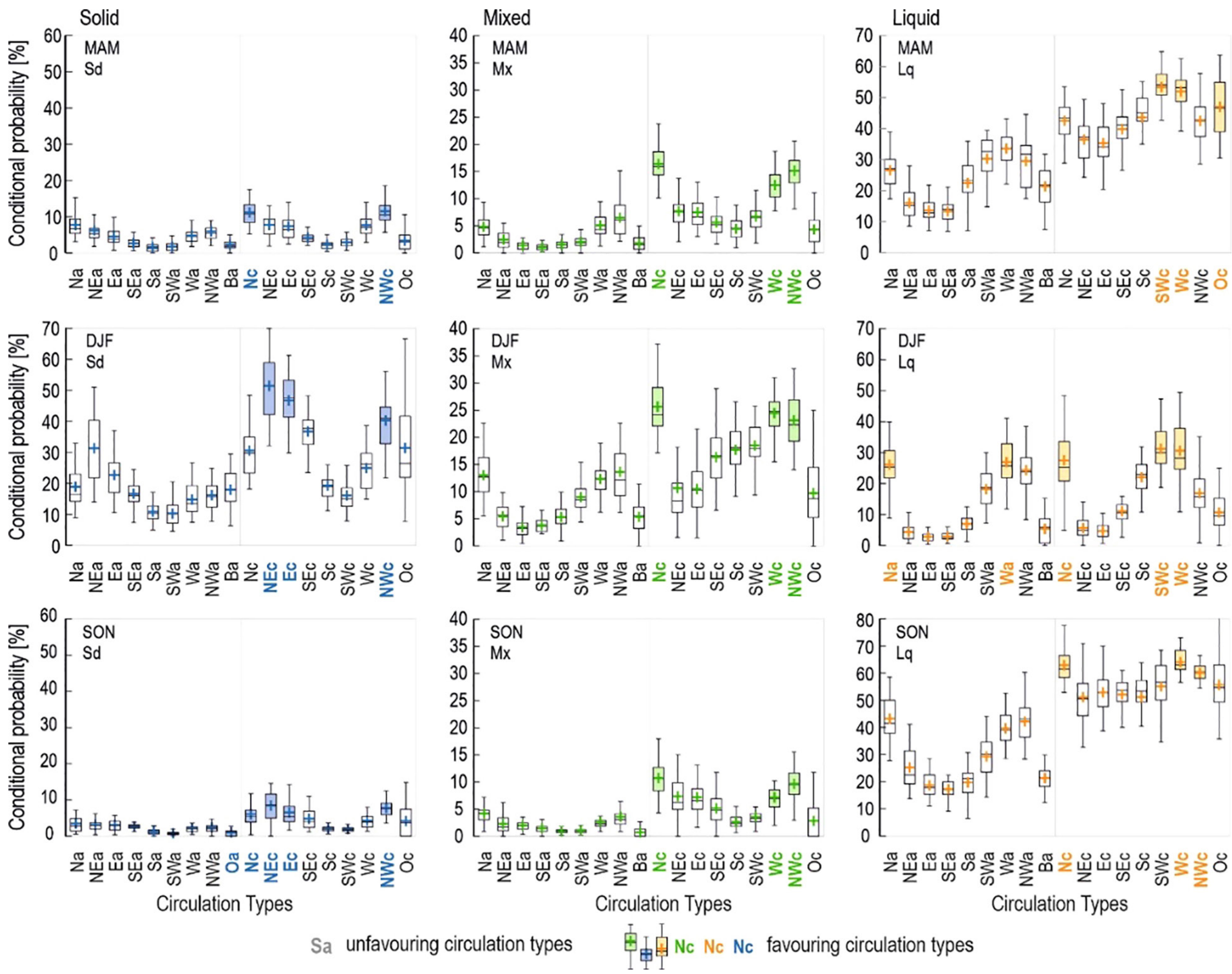


Fig. 3. Conditional probability of solid (Sd, blue), mixed (Mx, green) and liquid (Lq, orange) precipitation in circulation types, Poland, 1966–2020, a – boxplots: statistical distribution of the station probabilities of precipitation phases for each circulation type; cross – mean; horizontal line – median; box – 25th and 75the percentiles; whiskers – limits for outliers.

season, the average AT during Ec and NEc was substantially above the freezing point; however, on cold autumn days, it dropped to −1.3°C (Ec) or −3.0°C (NEc), thus favouring the occurrence of autumn snowfall. The air advection from the northern sector bringing cold air was found to be associated with heavy snowfall in many parts of central and southern Europe, including Poland (Bednorz 2008, 2011, 2013), the Iberian Peninsula (Merino et al. 2014, de Pablo Davila et al. 2021), northwestern Greece (Dafis et al. 2015), western Turkey (Baltaci et al. 2020) and the central Spanish Mediterranean area (Mora et al. 2016). Such an inflow of cold air masses bringing heavy snowfall was found related to extratropical cyclones travelling southwards in jet stream meanders formed by the disruption of the normal westerly flow (Tibaldi, Buzzi 1983, Barnes et al. 2014, Lehmann, Coumou 2015, Faranda 2020), blocking high-pressure systems close to Greenland and thus with advection of cold air from polar latitudes towards western Europe (North Atlantic Oscillation negative phase; Cattiaux et al. 2012) or a high-pressure ridge extending from the Azores towards Iceland or the British Isles with an inflow of cold air from Russia or Scandinavia to southern Europe (Buehler et al. 2011). Snowfall frequency was also slightly enhanced during anticyclonic type NEa in SON and DJF on a regional scale for the Baltic shore and southern and southwestern stations in the mountain and hilly areas due to sea-snowfall and orographic effects (Beniston et al. 2018, Lüthi et al. 2019). The probability of Sd for NEa reached 45–50% of days in the Baltic Sea and was higher in southeastern Poland (>50%).

In all the seasons, the probability of Mx was the highest on days with air advection from Nc (26–11%, depending on the season), followed by NWc (23–10%) or Wc (25–7%). In DJF, the NW advection brought relatively warm air to the lower troposphere (Nc: 0.2°C, Wc: 0.8°C, NWc: −0.8°C), resulting in a mixed phase due to the partial melting of snowfall. In transitional seasons when the average climate is warmer, NW advection brought the drop in AT to 5–6°C (MAM) and 6–7°C (SON) on average. During the coldest days, the AT was even lower, approaching the freezing point and favouring Mx. The probability of the Mx phase varied spatially much less compared to Sd and Lq (Fig. 4).

In all regarded seasons, the probability of Lq was amplified during air advection from the SW sector (Wc: 31–64%, SWc: 31–55%, depending

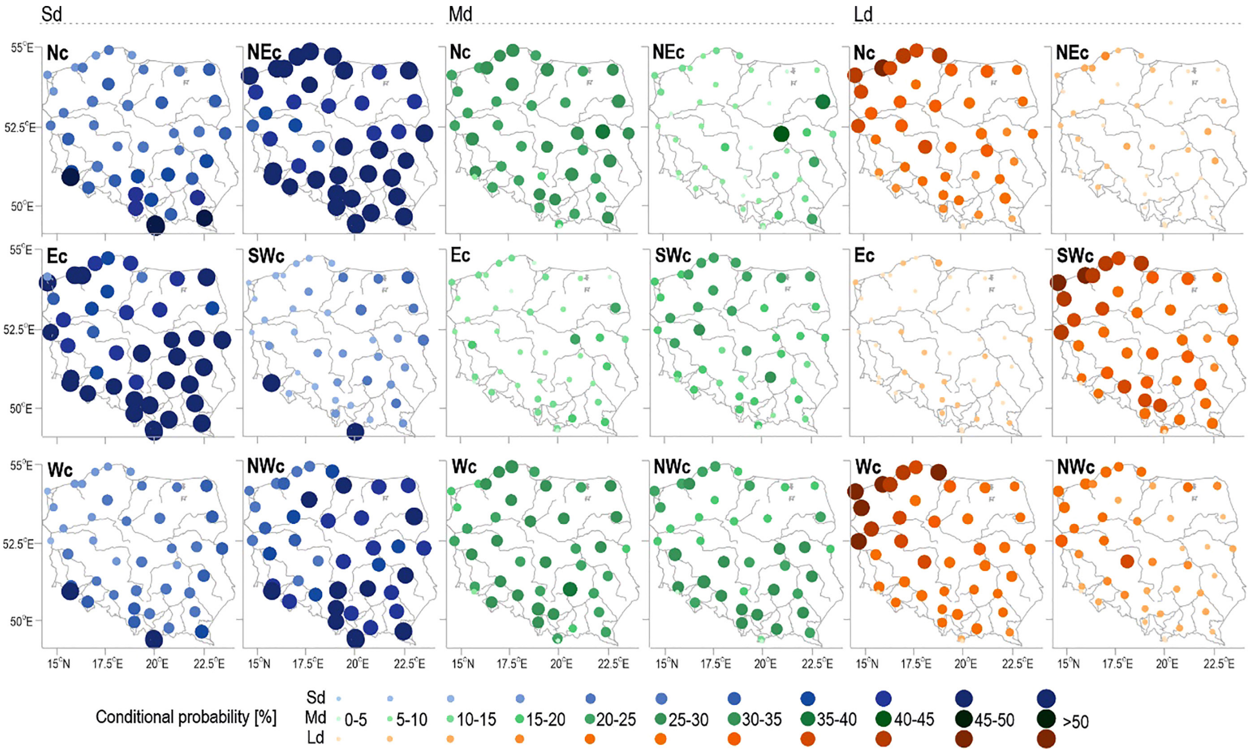


Fig. 4. Spatial distribution of the conditional probability of solid (Sd, blue), mixed (Mx, green) and liquid (Lq, orange) precipitation in cyclonic advective circulation types in DJF.

on season) and additionally from NWc in SON (60%). Air originating from over the Atlantic, particularly that inflowing during days with SWc and Wc, was warmer compared to most CTs, thus favouring rainfall. The NWc type was conducive to all precipitation phases in SON due to a wide range of its AT from below −3°C to 10°C. In DJF, the CP of rainfall was also enhanced during the advection of relatively warm air from the NW sector (average AT of approximately 0°C) during anticyclonic conditions (on average 24–26% of days with Wa experienced rain). The most interesting is type Nc, which favoured the occurrence of Lq and Mx in MAM, Sd and Mx in DJF and all phases in SON. This effect can be explained by seasonal and spatial variations in its daily AT that enable all phases to occur under proper thermal conditions. In SON – from −5°C to 10°C, in MAM from 7°C to −5°C, and in DJF from 2°C to −10°C.

## Tendencies in thermal properties of circulation types between the cold period 1966–1985 and the warm period 2001–2020

Some of the CTs were conducive to particular precipitation phases due to their various thermal properties; thus, they could have also contributed differently to long-term variability in the snowfall and rainfall probability due to various rates of warming and seasonal variability in their AT climatology. The box plots in Figure 5 present the distribution of average (1966–2020) station AT for particular CTs. Read and blue bars in Figure 5 show the averaged over stations range of change in air temperature between the cold period 1966–1985 and the warm period 2001–2020 for CTs for particular CTs from a seasonal perspective. These ranges indicate changes (hereafter tendencies) in the thermal properties of particular CTs in the research period. The spatial distribution of AT tendencies for cyclonic advective CTs at each station for the studied seasons in Poland is presented in Figure 6.

The rate of AT change between 1966–1985 and 2001–2020 varied depending on CT and season. The AT increased in most CTs; however, in some CTs, tendencies were minor or minor and negative. Several authors found that shifts in precipitation phases are the most significant at air temperatures close to the freezing point (Knowles et al. 2006, Feng, Hu 2007, Bintanja 2018, Łupikasza, Cielecka-Nowak 2020). Therefore, the most meaningful changes in AT for precipitation phases were those in DJF, particularly in CTs with average AT close to the freezing point, which, due to warming, crossed the 0°C threshold between the 20-year periods, i.e. SWa, Wa, NWa and Sc, SWc, Wc and NWc. In DJF, warming was the strongest (3.5–4°C) for NEc and Ec but only in southern Poland. AT increased at almost all stations by approximately 1.5–2°C during air advection from W sector (from N to SW), i.e., from the Atlantic under both cyclonic and anticyclonic conditions (Figs 5 and 6). The large AT increase during air advection from the NW sector can be related to accelerated warming in the high latitudes of the N Hemisphere (Serreze et al. 2009, Serreze, Barry 2011, Screen, Simmonds 2010). The smallest differences in AT between the 20-year periods were characteristic of air from the SE sector. During anticyclonic conditions, differences in AT for Ea and SEa were even negative (−0.4°C and −0.3°C). Anticyclonic E and NE advection was related to a high-pressure system with its centre north of Poland; thus, the source area of inflowing air masses was located in the central and northern part of eastern Europe, where winter air temperature showed decreasing trend in 2001–2019 (Perevedentsev et al. 2021).

In MAM, warming in anticyclonic types reached 1–2.3°C and was stronger than in cyclonic types (0.5–2.1°C) in most CTs. In anticyclonic types, the increase in AT between the 20-year periods was the largest for air from the southern sector (SWa–Sa–SEa). Moreover, the warming of air from the western sector (NWa, Wa, SWa) was stronger than that from the eastern sector (NEa, Ea, SEa). Considering cyclonic types, air temperature increased at the largest rate in SEc (2.1°C) in southern Poland and Sc (1.8°C) in southern and western Poland, followed by Nc (1.6°C) in southern and northwestern Poland and NWc (1.4°C) in southern Poland and most northern stations (Figs 5 and 6). Discrepancies in the rate of warming between cyclonic and anticyclonic types were the largest for air from the western sector, particularly from SW due to the configuration of the low- and high-pressure centres and various source areas of air masses during cyclonic (central and northern part of the Northern Atlantic) and anticyclonic advection (southern and southwestern Europe/The Atlantic).

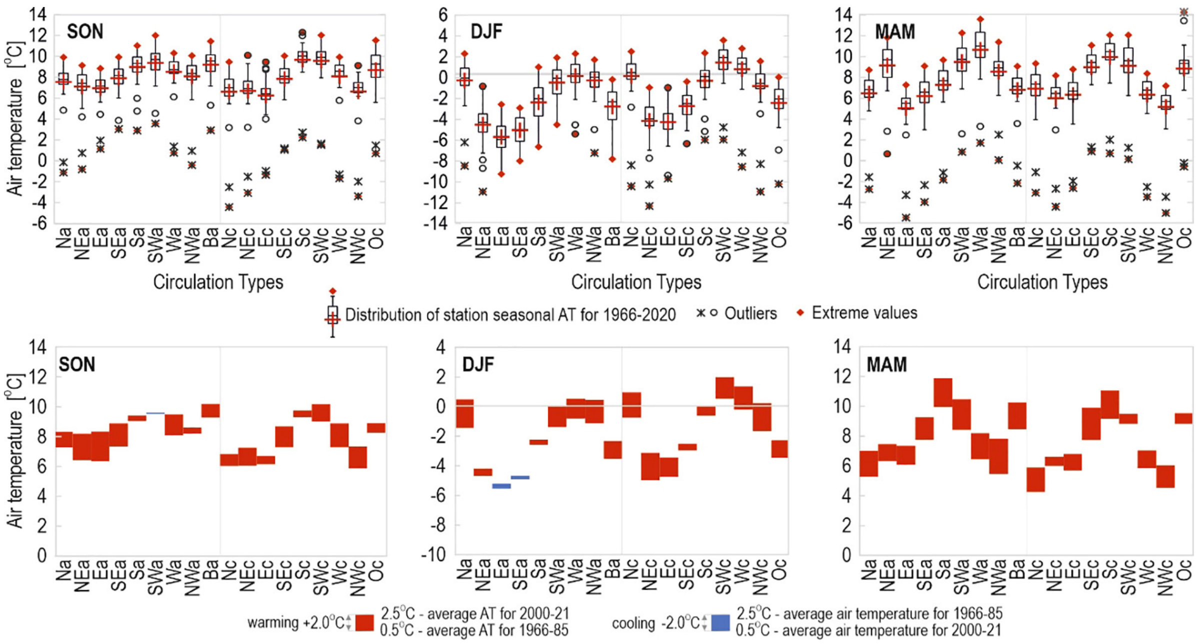


Fig. 5. Average air temperature for circulation types, box-plots –average seasonal station air temperature for the entire research period 1966–2020, red cross – mean; horizontal line – median; box – 25th and 75th percentiles; whiskers – limits for outliers (upper panel). Averaged over stations range of change in air temperature between the cold period 1966–1985 and the warm period 2001–2020 for circulation types (lower panel).

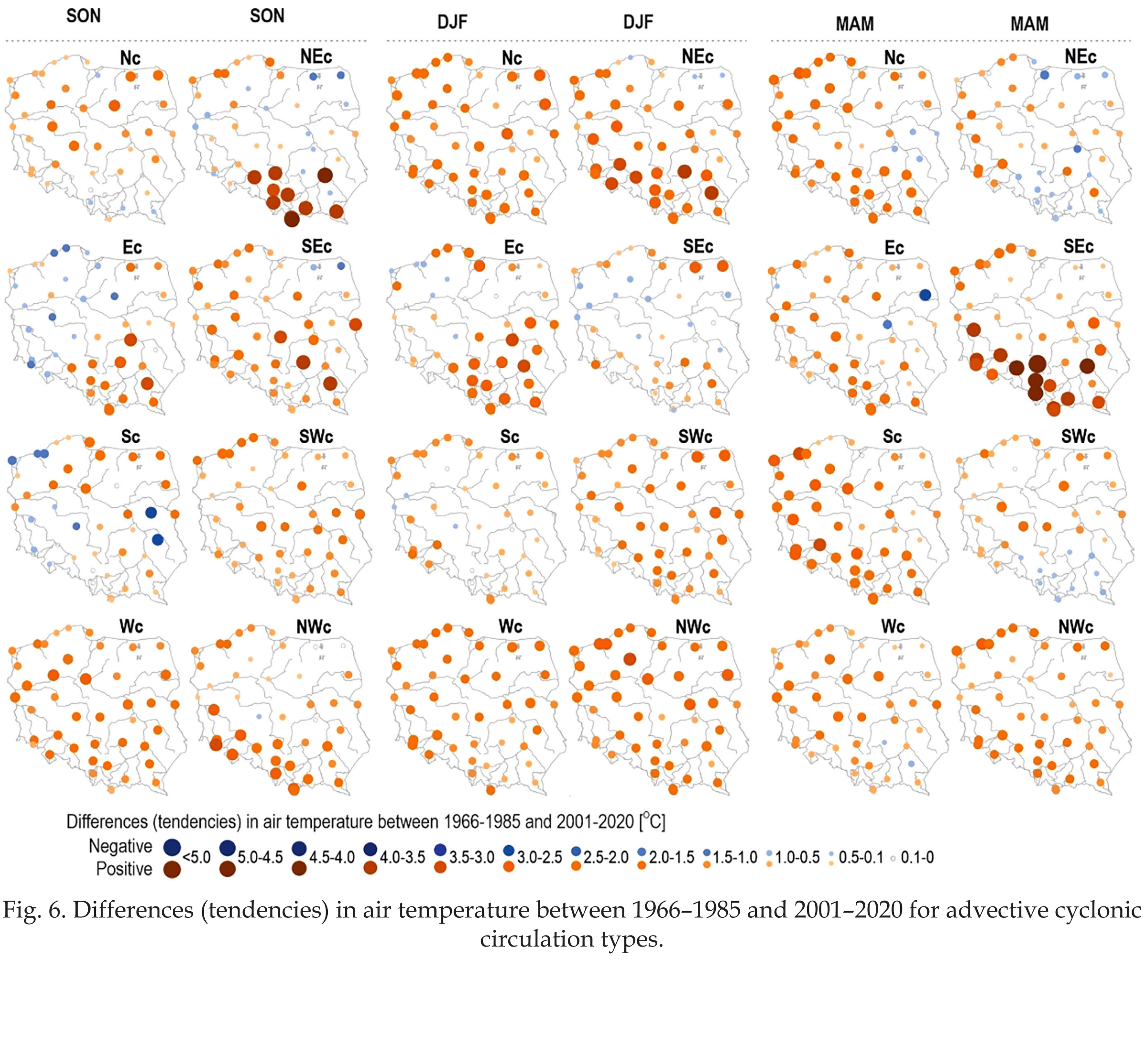


Fig. 6. Differences (tendencies) in air temperature between 1966–1985 and 2001–2020 for advective cyclonic circulation types.

In SON, the differences were largest on days with air advection from the E sector during anticyclonic conditions (NEa: 1.7°C, Ea: 2.0°C, SEa: 1.5°C) and from the W sector during cyclonic conditions – NWc: 1.4°C at southeastern stations, Wc: 1.6°C in central and southern Poland, SWc: 1.1°C in the central part of eastern Poland and at the Baltic Sea (Figs 5 and 6).

### Tendencies in the probability of precipitation phases between 1966–1985 and 2001–2020

The CP of precipitation phases for CTs in the cold (1966–1985) and warm (2000–2020) 20-year periods in the form of bars that are grey for the cold period and coloured for the warm period are presented in Figure 7. Differences in the length of bars indicate tendencies in the probability of precipitation phases depending on CT.

#### Winter

The probability of winter rainfall increased the most for the Nc type (by 14%) and the cyclonic air advection from the S to the NW sector (by 11–7%, depending on TC) (Fig. 7). These types significantly contributed to the spatial pattern of increasing trends in winter rainfall, which were the strongest in the northern and southern parts of Poland (Fig. 2). Increasing Lq trends in northwestern Poland (mainly in the Baltic Sea) were mostly due to the increased probability of rainfall in Nc, Wc and Sc, while in southern Poland, they were due to Nc, Sc and several other types – SEc, Ec, NWc (Fig. 8). The largest changes in Lq probability occurred in types with average AT above −4°C, particularly for that with AT close to the freezing point.

An increase in the Lq was accompanied by a decrease in the Sd, particularly in the Nc type (by 30%) in northern and southern Poland. The reason for the most rapid changes in that type, both an increase in Lq and a decrease in the Sd, was that the average AT for that type crossed the freezing point between the 20-year periods (from −0.7°C to 1.0°C, Fig. 5, lower panel). A similar effect was also found in areas/seasons with average ATs close to the freezing point (Knowles et al. 2006, Feng, Hu 2007, Łupikasza, Cielecka-Nowak

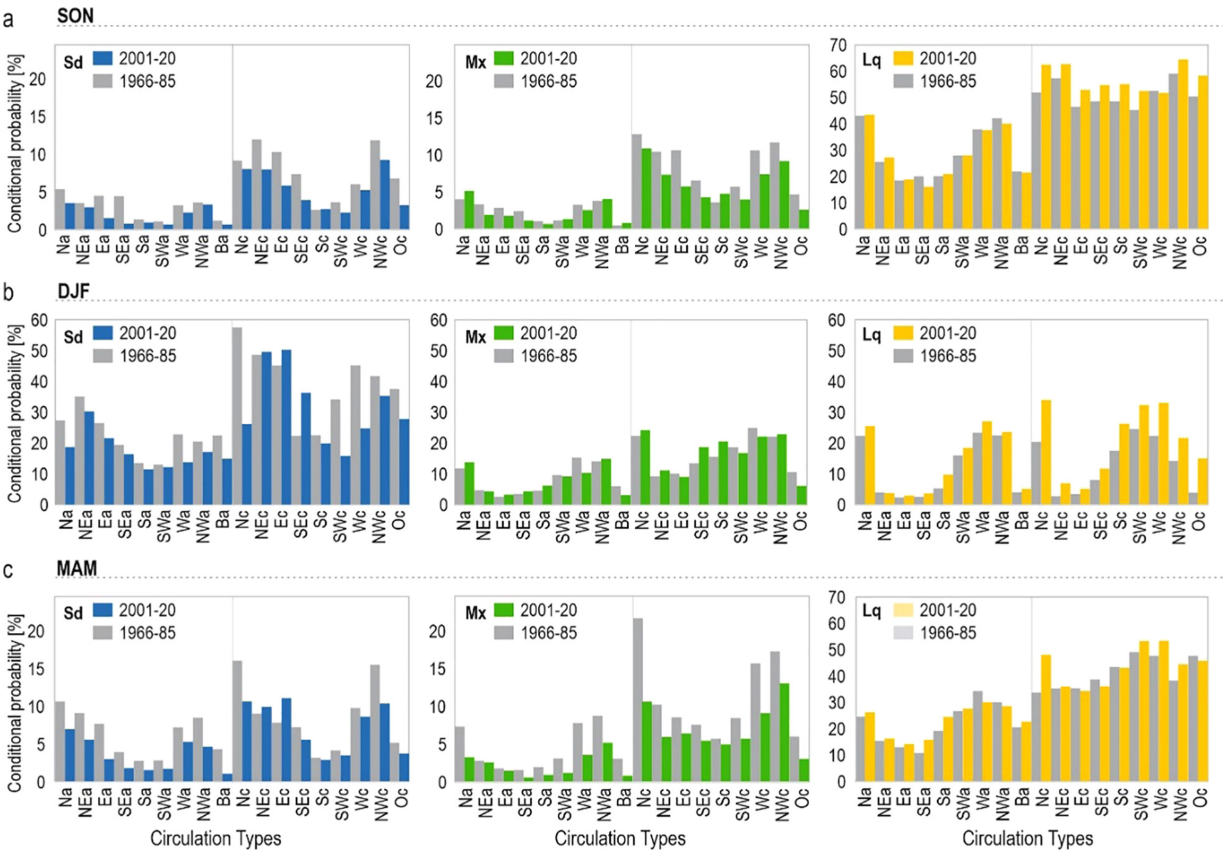


Fig. 7. Conditional probability of precipitation phases (Sd – solid; Mx – mixed; Lq – liquid) in the cold 1966–1985 and warm 2001–2020 periods averaged over stations for circulation types.

2020). The Sd probability also significantly decreased in Wc by 20% and SWc by 18%. On days with SWc, the decrease in Sd probability was largest in southern Poland. Spatial variability in the tendencies of snowfall was small for Wc (Fig. 8). Interestingly, the probability of snowfall increased in Ec in southern Poland and SEc almost in entire Poland (Fig. 8).

Rapid warming in NEc and Ec cold types in southern and western Poland (Figs 5 lower and 6) generated Sd tendencies of opposite direction in S and N Poland (Fig. 8) that resulted in no or little changes in snowfall probability on the country scale in these types (Fig. 7, DJF, Sd). Country-wide increase in snowfall probability in SEc is explained by little tendencies or even a decrease in AT between the 20-yers periods in that TC (Fig. 6). Generally, the increasing probability in snowfall from all eastern sector CTs can also result from decreasing or little changes in air temperature in Poland. These tendencies were related to cooling found in winter represented by January in the western part of Russia between 1976–2019 and 2001–2019, despite positive long-term trends in this area (Perevedentsev et al. 2021). Trends in winter Mx were non-significant due to various directions of tendencies in particular CTs.

**Spring**

In MAM, the probability of Mx decreased in almost all CTs. The spatial distribution of downward trends in the Mx frequency shown in Figure 2 was well explained by negative tendencies in the probability of this phase in Nc (11% in western and southern Poland) and Wc (6.5%, in central Poland (Fig. 9). Despite warming, in some CTs, particularly Sc and SEc, the probability of Mx increased. These increases, although small, repeatedly covered the southeastern stations and overlapped with decreasing Mx probability in Nc and Wc, finally resulting in non-significant trends in that part of the country (Fig. 2).

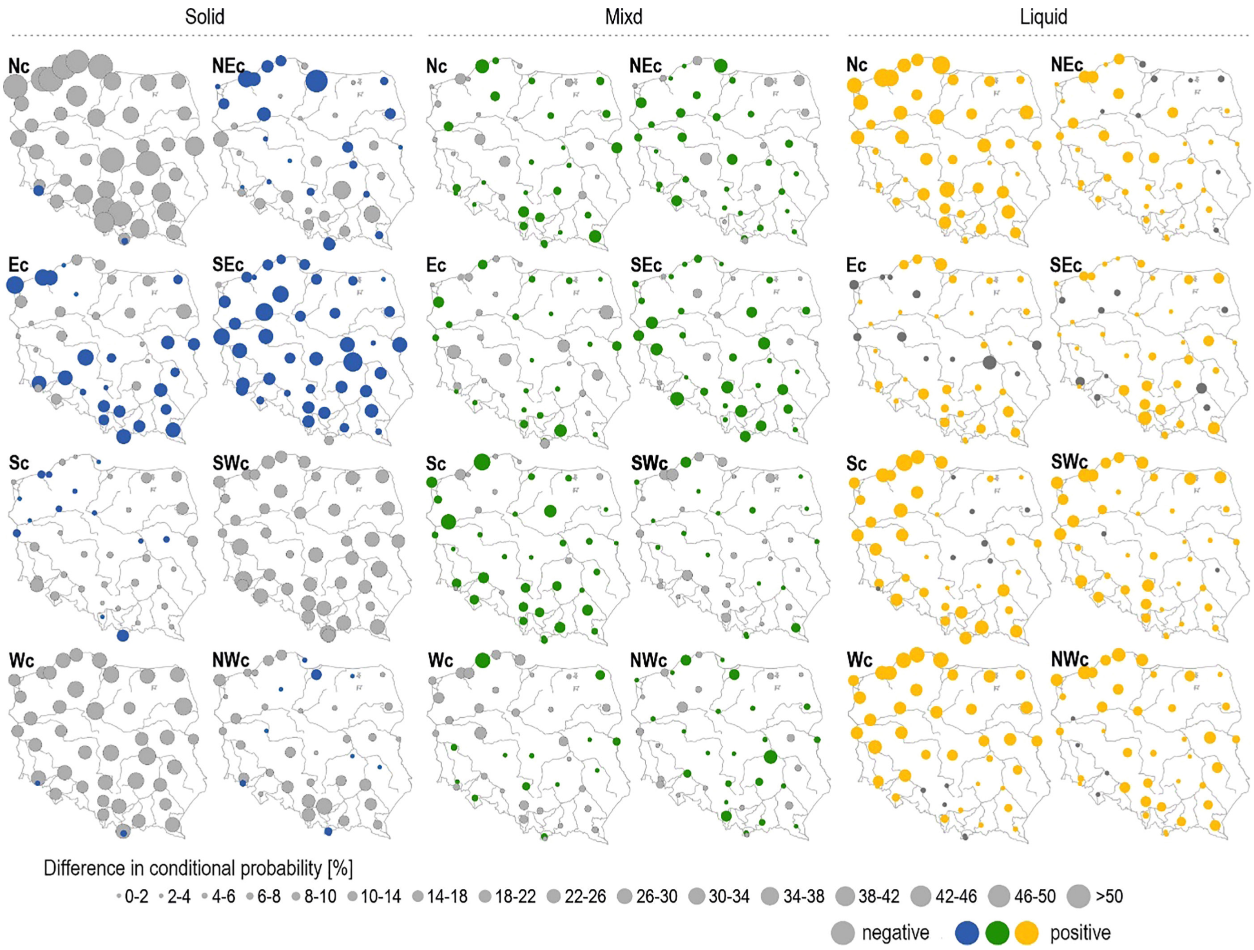


Fig. 8. Spatial distribution of tendencies (differences between the 20-year periods) in the conditional probability of precipitation phases for cyclonic advective circulation types in DJF.

The negative tendencies in the probability of spring snowfall were largest in Nc (5.4%) in southern and northwestern Poland and NWc (5.1%) and Ea (4.7%, not shown) in southern Poland (Fig. 9), where decreasing seasonal Sd trends were significant (Fig. 2). These three CTs largely explained the distribution of decreasing spring Sd trends, particularly at the southernmost stations and at some stations in southeastern Poland. The weak or lack of Sd trends at some stations resulted from opposite tendencies – negative and positive in Sd probability depending on CT. In two cyclonic CTs – Ec and NEc – the probability of snowfall increased (Fig. 9). Increasing tendencies in Mx also occurred in other TCs, however only at some stations and they were small (Fig. 9).

Tendencies in the Lq probability varied depending on the CT, but the spatial patterns for particular types were clear. The probability of rainfall increased in Nc (by 14.4%), NWc (by 6.2%) and Wc (by 5.8%) and slightly decreased in Ec and SEc by no more than 3% in central and northern Poland. In other CTs (NEc, Sc, SWc), the patterns were more complicated (Fig. 9). Clear tendencies in Lq conditional probabilities were also found in some anticyclonic CTs (not shown) – increasing in Sa (by 5.2%), SEa (by 5.0%), and SWa (by 1%) and decreasing in Wa (by 4.3%).

**Autumn**

In cyclonic types, the largest decrease in the Mx probability was found in Ec (4.8%), Wc (3.2%) and NEc (3.0%). These types contributed to decreasing trends in Mx frequency in the southern (Ec, NEc) and northern (NEc, Wc) parts of western Poland. However, in this season, the spatial pattern of Mx tendencies in no CT (Fig. 10) was similar to the pattern of seasonal Mx trends (Fig. 2). Thus, several CTs could have contributed to trends in the frequency of Mx shown in Figure 2 including Nc, SWc and Wc in northwestern Poland and by SEc and NWc in southern Poland.

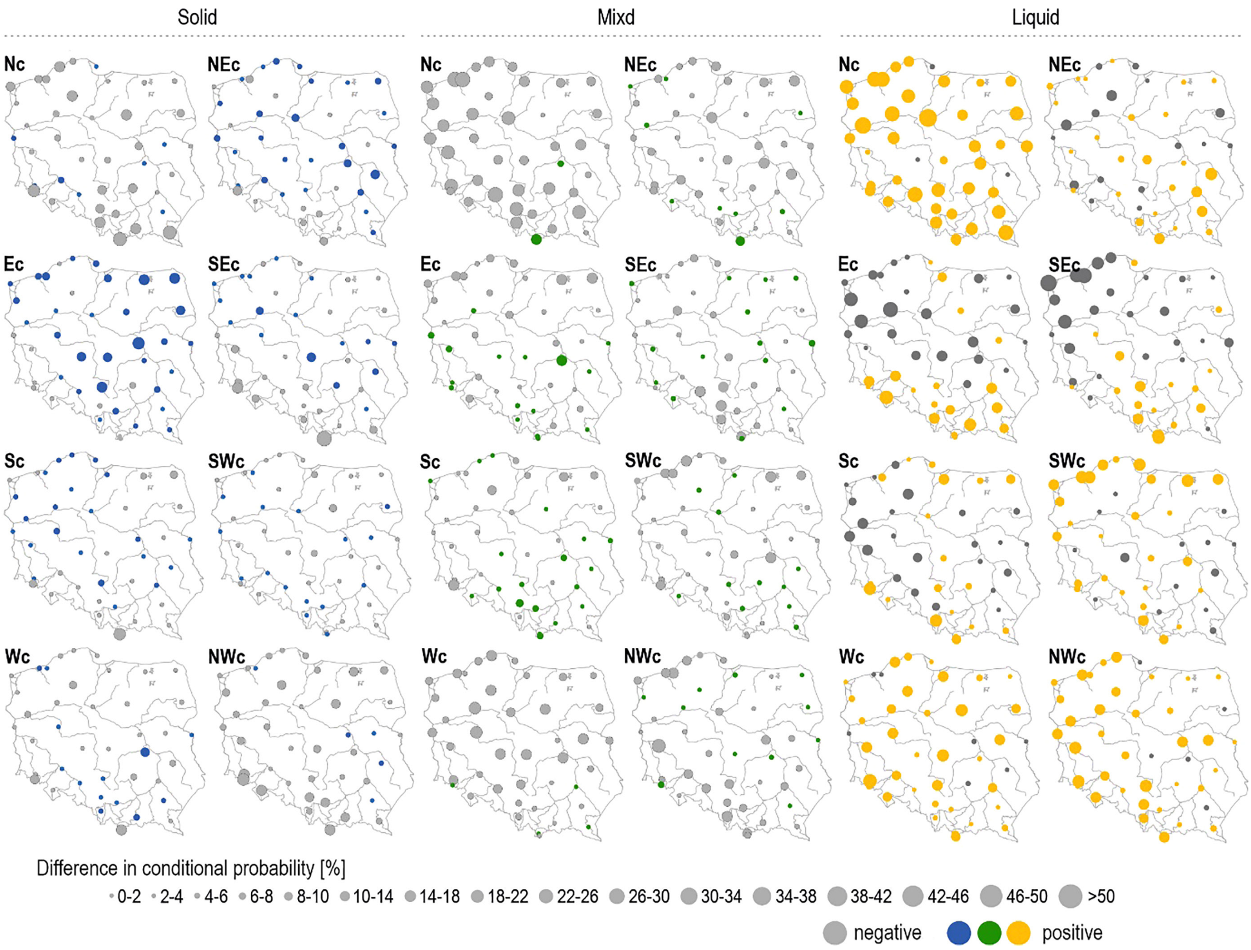


Fig. 9. Spatial distribution of tendencies (differences between the 20-year periods) in the conditional probability of precipitation phases for cyclonic advective circulation types in MAM.

Negative trends in SON snowfalls were mostly weakly significant and clustered in southern Poland and were related to the diminishing Sd probability (by 4–3%) in cyclonic types of the eastern sector (NEc, Ec, SEc) (Fig. 10) and, to a lesser degree, in NWc. The decrease in Sd probability was weakened by contrary tendencies in Nc, Sc and Wc (Fig. 10), thus producing small trends in Sd at southern stations (Fig. 2). In other parts of Poland, tendencies were weak and of various directions depending on CT, contributing to non-significant trends in Sd frequency.

The spatial pattern of tendencies in Lq probability was clear; however, these tendencies were not large compared to the average probability of rainfall in that season (10–15% of average) and did not result in significant seasonal Lq trends. Tendencies were positive in most of the cyclonic types, except for Wc. The probability of rainfall increased in southern Poland during air advection from the southeastern sector under the influence of cyclone (Ec, SEc, Sc) and for Nc, and in northern Poland during NEc (Fig. 10).

## Conclusions

In Poland, the direction of trends in the frequency of precipitation phases coincided with current warming; thus, in the research period 1966–2020, the frequency of the Sd and Mx decreased, while the frequency of the Lq increased. Trends in the solid phase were significant and common in DJF and weakly significant in MAM, while in SON, they were weak and covered only southern stations. The Lq frequency increased in winter while Mx was rarer in transitional seasons.

The occurrence of particular precipitation phases depended on the direction of air advection and the type of baric centre (cyclone, anticyclone) over Poland due to various thermal properties of air masses inflowing from various directions

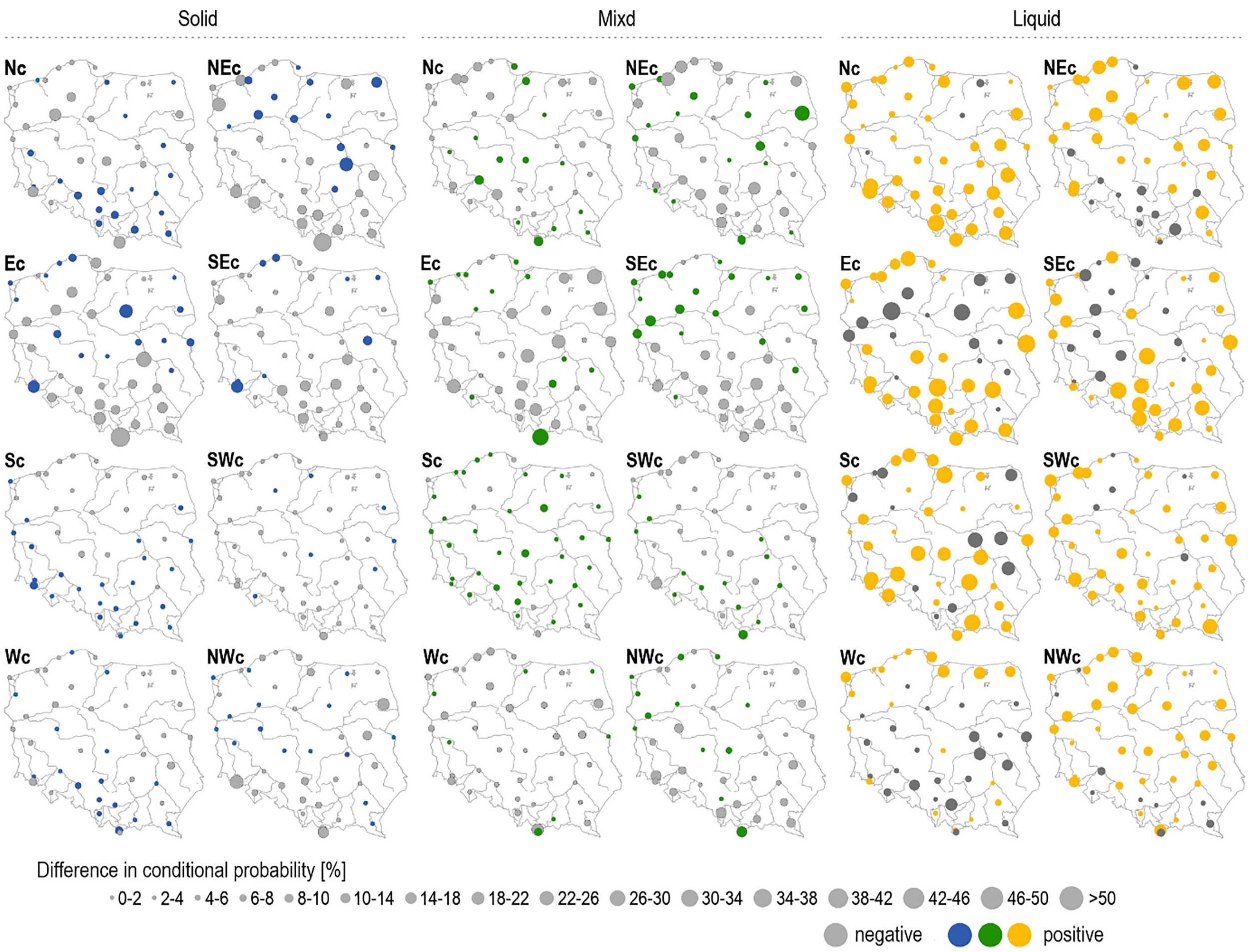


Fig. 10. Spatial distribution of tendencies (differences between the 20-year periods) in the conditional probability of precipitation phases for cyclonic advective circulation types in SON.

and thus source areas. This resulted in various air temperatures during particular CTs, which drove changes in the probability of precipitation phases.

The probability of all precipitation phases in cyclonic CTs was larger than that in anticyclonic CTs, which are known to be less prone to convection. The Sd was more frequent on days with air advection from the NE sector (NEc, Ec) and NWc in winter and from Nc in transition seasons. In these types, snowfall probability was high in the whole country, but it varied spatially, being highest in the hilly and mountain areas and the Baltic Sea (NEc and Ec). These types were conducive to snowfall due to the lowest air temperatures compared to other types. At the Baltic Sea during the NEc and Ec types, there is an intrusion of very cold air that warms over the warmer water and induces convection, thus increasing the probability of snowfall. This lake/sea-snowfall effect is known to generate extreme snowfall (Suriano and Leathers 2017, Bednorz et al. 2022). The average AT during NWc in DJF was relatively high compared to the other types; however, on extremely cold days, it dropped far below freezing, favouring the occurrence of snowfall.

Mixed precipitation was most likely on days with air advection from the northwestern sector (Nc, NWc, Wc) due to ATs close to freezing in DJF and coldest outliers and extremes compared to other CTs in transitional seasons. Air advection from the southwestern sector (SWc, Wc – warmest in winter) was most conducive to rainfall. In SON, the Nc and NWc types were conducive to all precipitation phases due to the widest range of air temperatures that occurred on days with these types.

In most CTs, the air temperature increased between 1966–1985 and 2001–2020 but at various rates depending on CT. The rate of warming depends on the configuration of the low- and high-pressure centres, which determine the movement of air masses inflowing from various source areas. The type of baric centre also played a role. The spatial distribution of the warming was also specific for particular types and helped explain the spatial variability in the rate of trends in precipitation phases. Despite global warming, during some types, air temperature exhibited little increase or even slight cooling.

The tendencies in the probability of precipitation phases between 1966–1985 and 2001–2020 were mostly related to the rate of changes in air temperature in particular CTs and in winter to the AT of the CTs.

The spatial pattern of decreasing snowfall trends was explained by the distribution of tendencies in snowfall probability in Nc, Wc and SWc in DJF; Nc, NWc and Ea in MAM and NEc, Ec and SEc in SON. In some CTs, the probability of snowfall changed little or slightly increased – Ec and NEc in MAM, Ec and SEc in DJF and Nc, Sc and Wc in SON either throughout the country or in several regions.

Tendencies in winter rainfall probability were the largest in types with air temperatures close to freezing (Nc, Sc, SWc, Wc) and large warming and smallest in the coldest types. Cyclonic CTs of W and E sectors contributed to the spatial distribution of trends in winter rainfalls, in northern and in southern Poland, respectively.

Tendencies in the probability of Mx phase were largest in types conducive to its occurrence – Nc, NWc, Wc, and these types accurately explained the spatial pattern of trends in the Mx frequency in MAM, although warming in these CTs was less intense. In SON, several CTs contributed to trends in the frequency of Mx.

Differences between the spatial distribution of snowfall and rainfall trends and seasonal air temperature trends were due to various warming rates and average ATs for particular CTs. These features governed the spatial distribution of diminishing snowfall frequency and increasing rainfall frequency, particularly in DJF. Cold synoptic types can still bring snowfall even in transitional seasons unless the daily AT crosses the threshold for snowfall occurrence.

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## Authors' contribution

E.Ł. – study conception and design, identification of precipitation phase, analysis and interpretation of results, and manuscript preparation; Ł.M. – data collection, editing the manuscript; Q.B.P. – calculation, editing the manuscript, proofread

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