Erratum: Winter cyclone frequency and following freshet streamflow formation on the rivers in Belarus (2013 Environ. Res. Lett. 9 095005)

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In the original article, figure 1 is incorrect. The correct figure is as follows:

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Winter cyclone frequency and following freshet streamflow formation on the rivers in Belarus

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Abstract
We studied long-term fluctuations of streamflow and occurrence of extreme phenomena on the rivers of Belarus during the post-World War II period. It was found that formation of annual runoff within the nation has no constant tendencies and varies from year to year. At the same time, analysis of intra-annual distribution of streamflow reveals significant changes since the 1970s, first of all, increase of winter and decrease of spring streamflow. As a result, the frequency of extreme floods has decreased. These changes in water regime are associated with climatic anomalies (increase of the surface air temperatures) caused by large-scale alterations in atmospheric circulation, specifically in trajectories of cyclones. During the last two decades, the frequency of Atlantic and southern cyclones has changed and caused decreasing of cold season storms and extreme phenomena on the rivers.

Keywords: atmospheric circulation, cyclone, climate, streamflow, flood

1. Introduction
The hydrological regime of the rivers in Belarus is controlled by quantity and temporal distribution of precipitation (Loginov 1996, Nekrasova 2004). In the cold season, this precipitation depends upon the cyclones passing through its territory (Babkin and Klige 2005). The cyclones originate in different regions and arrive from different directions to the country. They are formed under various hydrometeorological conditions and may generate drastically different moisture regimes (Krichak 1956). For example, south cyclones during the winter season bring considerable precipitation and are associated with strong winds and snowstorms. The Atlantic cyclones in winter bring to Belarus mild weather with thaws and perennial precipitation. Frequencies of cyclones of various genuses and trajectories control formation of spring freshet and corresponding floods.

Development of tools for automatic definition of cyclones (Rudeva and Gulev 2007, Tilinina et al 2013) has given new possibilities of research of climatic variability of the atmosphere. Gulev et al (2001) analysed cyclonic activity in the winter season over the Northern hemisphere. They found that the total number of cyclones has decreased over the central Atlantic Ocean but increased significantly in the areas of the Icelandic Low and in the European Arctic. Historically, numerous studies (see, Flohn et al 1992, Schinke 1993, Stein and Hense 1994, Haak and Ulbrich 1996, Lambert 1996, Sickmoller et al 2000, McCabe et al 2001, Zhang et al 2004) came to similar conclusions. Further studies of cyclones frequency in the northern and central Europe documented increases in the quantity of northern cyclones,
especially during the winter season that have led to precipitation increase in northern and decrease in the central Europe (Sepp and Jaagus 2002, Sepp 2005 and Post et al 2002).

The detailed assessment of climatic change for northern Europe including Belarus was provided by the BACC et al (2008). Within former USSR territory (including Belarus) similar studies were conducted by Drozdov and Grigor’eva (1971), Kobysheva et al (1981), Drozdov (1990), Kobysheva (2001), Kitaev (2002) and for Belarus by Budyko, Kajgorodov, Dmitrenkova (2002), Golberg (2003), Kovrigo (2001), Loginov (1992, 1996, 2003 and 2008), and Melnik and Komarovskaya (2010, 2011). In particular, Loginov (2008) has established dependences of streamflow fluctuations of Belorussian rivers with different macro-circulation types of atmospheric circulation over the country.

Streamflow in the Baltic Sea Basin is well studied (Klavins et al 2002, 2008, Hisdal et al 2003, 2007, Lindstrom et al 2006, Kilkus et al 2006, Reihan et al 2007, Kriaucieniene et al 2008, 2012, Szwed et al 2010, Döll and Müller Schmied 2012, Babkin and Postnikov 2000 and Babkin et al 2004). For example, Klavins et al (2002) documented a recent decrease of minimal streamflow on the main rivers in Latvia; these results correlate well with those for the Belorussian rivers.

For Belarus the key findings about the hydrological cycle were made by Volchek (1991, 2001 and 2006) as well as by Grinevich and Pluznikov (1997), Nekrasova (2004), and Danilovich and Trofimova (2007). In particular, while assessing precipitation and streamflow patterns over Belarus, Loginov and Volchek (2006) partitioned its territory into two distinctive regions: the northeastern part with increasing annual precipitation and the southwestern part where precipitation has decreased. Similar results were obtained by Jaagus (2009) who used principal component analysis to regionalize the precipitation pattern over the Baltic Sea Basin associated with large scale atmospheric circulation characteristics. For the winter season, these researchers reported differences of the large-scale circulation impact on precipitation in the northern and southern halves of Belarus.

We considered extreme events on the hydrological station when certain water level threshold is exceeded (individual threshold at each hydrological station) that causes inundation of the adjacent territory. Studies of the extreme phenomena on the rivers of Belarus were summarized by Nezhihovsky (1998). He developed a classification of floods using scales of river water level increase and divided floods into three categories: outstanding, large and small. Thereafter, the extreme hydrological phenomena on the rivers of Belarus were studied by Loginov et al (2010) and the reference book of the extreme phenomena over the territory of Belarus was prepared by Golberg (2002). This reference book was also used in the present study. However, comparing to the studies for the Baltic Sea Basin, the analyses for Belarus remain more sketchy and further studying of hydrometeorological processes and extreme phenomena on the rivers is still warranted. The goals of this study are:

- to analyse winter (DJF) cyclone trajectories of different origin over Eastern Europe, to count their numbers during the past sixty years, and to estimate trends in these numbers,
- to relate the cyclone counts trends with dynamics of winter surface air temperature and precipitation in Belarus, and
- to connect the changes in cyclone frequency and meteorological conditions with freshet extreme phenomena (flood during spring snowmelt) on Belorussian rivers.

For better understanding of the describing processes over Belarus we put below a brief description of its main river basins. Belarus is situated in the west of the Great East European Plain. Its territory belongs to the Baltic (47%) and Black (53%) Sea Basins. Three main rivers and their tributaries pass through the country. The Zapadnaya Dvina (Daugava) River inflows in the east from Russia and outflows to Latvia. The Neman River has its source in the centre of Belarus and outflow to Lithuania. These river basins belong to the Baltic Sea Basin. The annual outflow to the neighbouring countries is on average 13.9 km³ to Latvia via the Zapadnaya Dvina River and 9 km³ to Lithuania via Neman.

The Dnepr River comes to the northeast Belarus from Russia, crosses the country southward, and outflows to The Ukraine. The Dnepr’ largest tributary is the Pripyat’ River. This river is considered as a separate river basin. The Pripyat’ River has its source in the southwest of the country and passes to the southeast where it outflows to The Ukraine. The Dnepr and Pripyat’ Rivers belong to the Black Sea Basin. On average, their annual outflow to The Ukraine is 31.9 km³.

### 2. Data and methods

#### 2.1. Cyclone data

We use cyclone tracks derived with the cyclone tracking algorithm developed in the PP Shirshov institute of Oceanology of the Russian Academy of Sciences (Zolina and Gulev 2002) using two reanalyses: NCEP/NCAR (Kalnay et al 1996, ERA Interim Simmons et al 2007, Dee et al 2011). Also we used a third dataset of cyclones based on

| Reanalysis | Spatial resolution of output | Spectral/vertical resolution | Time resolution of output |
|------------|-----------------------------|-----------------------------|---------------------------|
| NCEP/NCAR (1949–2012) | 2.5° × 2.5° | T62L28 | 6 hours |
| ERA-Interim (1979–2011) | 0.75° × 0.75° | T255L60 | 6 hours |
| 20 century reanalysis (1949–2011) | 2° × 2° | T62L28 | 6 hours |
the 20th Century Reanalysis v2 (Compo et al. 2011). Basic characteristics of these three reanalyses are provided in Table 1.

The automatic tracking procedure for the NCEP/NCAR (NCEP) and Era-Interim reanalysis was provided by Gulev and his colleagues (2001 and 2002). The cyclone centres are defined automatically as a minimum pressure with respect to the eight neighbour points, and then the tracking is carried out by an interactive procedure. The output of the tracking includes the coordinates, time, and corresponding sea level pressure (SLP) values (Gulev et al. 2001). Later Zolina and Gulev (2002) suggested the approach to improve the mapping accuracy which is based on interpolation of time steps of 10 min (36 points per one 6-hourly step). This improvement allowed obtaining a more accurate dataset of cyclone tracks.

The 20 Century Reanalysis version 2 (20cR2) dataset contains synoptic-observation-based estimates of global atmospheric variability spanning 1871–2012 period and derived using only observations of synoptic surface atmospheric pressure and prescribed monthly SST and sea-ice distributions as boundary conditions for the atmosphere. Trajectories of cyclones are presented as the ensemble of 56 trajectories (i.e. 56 variants of tracks for each cyclone). These 56 variants of each cyclone represent a cloud of cyclones that were generated with different initial boundary conditions. We defined an average position from a dispersion of points of these cyclonic trajectories.

We tested several variants of the research domain for analyses of cyclone tracks entering the domain (Figure 1). Finally, we selected to use the borders of the first, largest domain to be elongated westward in order to take into account the entire cyclone path originated in the North Atlantic sector (domain 1 within 5–45° N and 40–65° E). Atlantic cyclones mostly come from the West and their number account for 60–70% of all cyclones coming to Belarus. This selection allowed us also to synchronize trends in the cyclones tracks over Belarus with those over Central Europe.

Thereafter, we narrowed the study region to 20–35° N and 48–60° E (domain 2). This allowed providing more accurate estimates of the cyclones’ influence on the precipitation pattern over Belarus. This is a major domain used in our study. The choice of the domain size is based on results of the cyclone radius influence studies by Zolina and Gulev (2002) who used an area expanded by 555 km in all directions from the focus territory (under recommendation by Sinclair 1994). Further, they have established that the radius of cyclone influence fluctuates from 300–400 km to 900 km. Therefore in the present study we have added the third region limited 50–56° N and 23–33° E (domain 3).

For the analysis of influence of cyclone activity on formation of hydrometeorological conditions we accounted for the trajectories that have at least one point within the study domain.

We estimated the total number of cyclones and separately the number of cyclones with various origins—West, North,
South and Scandinavian for winter season (December–February). We also count cyclones of different origin with atmospheric SLP in the centre below 1000 hPa and selected the minimum SLP from each cyclone track over the study domain. We considered cyclones that pass the region several times over the same month as single entries.

We sampled the cyclone tracks by directions (figure 1). Then we chose cyclones which have arisen in northern Atlantic and among this group distinguished Scandinavian cyclones, with the origin north of 65° N, which moved from Scandinavia (the North-West) in a southern direction.

We defined the second type of cyclones (Atlantic origin) as the West cyclones which trajectories lie within 50–56° N moving in a zonal direction and crossing borders of the study domain from the west. Cyclones of the third group from Atlantic move as West cyclones but their pathways are within 56–65° N. This type of cyclones differs insignificantly from previous and could be considered as a version of West cyclones. The fourth large group of cyclones which we studied are cyclones of a southern origin. This kind of cyclones represents a special interest as they bring rainy weather with a considerable quantity of precipitation, and often cause the occurrence of dangerous phenomena. We defined South cyclones according to Gulev et al (2001), as lows formed to the south of 47° N and east of 0° meridian, and entering into our study domains from the South, Southwest or Southeast.

This partition does not include the entire variety of the cyclone trajectories over Europe. We encountered the cyclones characterized by northern origin (north of 65° N) that enter the territory of Belarus from the northeast bringing cold Arctic air masses. But the frequency of such cyclones is very low and in the present study they are not considered.

Sampling cyclones according to their direction is highly disputed. We applied the scheme of cyclones movement by Krichak (1956) and analysing weather maps of distribution of the trajectory of cyclones during winter for the period of 63 years from 1949 to 2012. Krichak wrote in detail about typical distribution of these cyclones. Singling out some West cyclones (we rename them as North cyclones) is the result of grouping of isolated sub-group of cyclones, which was traced on the map and was formed as a separate group. It is clearly seen, that these cyclones do not differ from West ones according to their climatic characteristics; but their trajectory, passing Belarus northward of its northern borders, motivated us to analyse this sub-group separately. The finding of an increase in the number of North cyclones in the absence of changes in the number of West cyclones, confirms the legitimacy of our choice.

### 2.2. Meteorological data

We used precipitation, surface air temperature and snow water equivalent data (the maximum values of snow water equivalent, which are usually observed in the end of winter season before snowmelt) from stations within Belarus. We

- analysed monthly and seasonal (December–February) precipitation totals; defined their trends, calculated net

| № | Meteorological stations | Hydrological stations | Catchment, km² |
|---|-------------------------|-----------------------|----------------|
| 1 | Vitebsk 1 .Zapadnaya Dvina (Daugava) (Vitebsk) | | 27 300 |
| 2 | Polotsk 2 .Zapadnaya Dvina (Daugava) (Polotsk) | | 41 700 |
| 3 | Verhnedvinsk 3 Disna (Sharkovschina) | | 4720 |
| 4 | Minsk 4 Neman (Stolbtsy) | | 3070 |
| 5 | Lida 5 Neman (Belitsa) | | 16 700 |
| 6 | Grodno 6 Neman (Grodno) | | 33 600 |
| 7 | Naroch 7 Oshmyanka (Bolshe Yatsyny) | | 1400 |
| 8 | Novogradok 8 Schara (Slonim) | | 4860 |
| 9 | Prujany 9 Ryta (Malye Radvanich) | | 968 |
| 10 | Brest 10 Lesnaya (Kamenets) | | 1920 |
| 11 | Orsha 11 Dnepr (Orsha) | | 18 000 |
| 12 | Mogilev 12 Dnepr (Mogilev) | | 20 800 |
| 13 | Zhlobin 13 Dnepr (Zhlobin) | | 30 300 |
| 14 | Borisov 14 Dnepr (Rechitsa) | | 58 200 |
| 15 | Bobruysk 15 Berezina (Bobruysk) | | 20 300 |
| 16 | Slavgorod 16 Sozh (Slavgorod) | | 17 700 |
| 17 | Gomel 17 Sozh (Gomel) | | 38 900 |
| 18 | Zhitkovichi 18 Pripyat (Chemichi) | | 74 000 |
| 19 | Vasilevichi 19 Pripyat (Mozyr) | | 101 000 |
| 20 | Pinsk 20 Goryn (Vikarovich) | | 27 000 |
| 21 | Lelchitsy 21 Ubor (Krasnobreje) | | 5260 |
| 22 | Mar’ina Gorka 22 Ptich (Luchitsy) | | 8770 |
| 23 | Velikie Luki 23 Pripyat’-Lyubya’ | | 6100 |
| 24 | Smolensk 24 Sluch-Sarny | | 13 300 |
| 25 | Bryansk 25 Goryn-Derajnoe | | 9160 |
| 26 | Warsaw 26 | | |
| 27 | Byalostok 27 | | |
| 28 | Vilnius 28 | | |
| 29 | Daugavpils 29 | | |
For this study, we used daily meteorological data of 29 stations in Belarus and neighbouring countries for the period from 1949 to 2012 (table 2, figure 2).

2.3. Hydrological data.

Hydrological data (at 25 stations that have slightly different locations, table 2, figure 2) represent the minimal discharges of winter low-water period and maximum discharges of spring floods. They were used to define trends, net change, and to analyse spatial distribution of minimal and maximum streamflow change within Belarus in winter and spring. Separately, we assessed dangerous thresholds in the river water levels and the frequency of floods of various severity (Golberg 2002).

The numbers of the hydrological stations in the table correspond to the numbers on the map in figure 2.

Observations availability in our data sets varies. Our main research focus was on the influence of cyclonic activity on formation of the extreme phenomena on the rivers of Belarus. Therefore, we carried out research only from 1949 (the beginning of the NCEP/NCAR dataset) to 2012 and limited our analysis only to the winter period (December—February). This was done because in the winter season the main factors are formed that define high spring floods (thickness of snow pack and water-supply in the snow, presence of ice crust, frozen soil, and thickness of ice cover on the rivers and jams).

2.4. Method used for analysis of temporal changes in time series

For all analysed time series, we used the Mann–Kendall (MK) test (Kendall 1970) to reveal statistically significant trends at the 0.05 or higher statistical levels. Specifically, we tested null hypothesis, $H_0$, that ‘no systematic trend in time-series is present’ against alternative hypothesis, $H_1$, that increasing or decreasing tendencies are presented. Thereafter, we applied the least squares method (LSM) to estimate the mean rates of changes for those time-series which showed statistically significant changes (in this study—North and South cyclones, as well as meteorological and hydrological characteristics). Additionally, we used robust linear regression Sen’s estimator (Sen 1968) for the same purpose but found that the use of
LSM and Sen’s estimators for our time series give practically the same mean rate of change values.

3. Results

3.1. Cyclone frequency, winter

We examined cyclone trajectories in three reanalyses, namely: NCEP/NCAR, ERA-Interim and 20cR2. We counted both the total number of cyclones and, separately, the number of Scandinavian, North, West and South cyclones during winter season, DJF. As a result, we determined mean counts of cyclones of different origin and intensity within three domains (table 3) and the number of cyclones during the winter season (see, figure 3).

Table 3 shows that climatologies of these numbers vary by reanalysis. It could be explained by several factors such as resolution, data assimilation procedure, parameterization scheme, and different observations available for each reanalysis. Two of them (NCEP and 20cR2) have the same time period but quite different climatologies. The most important factor influenced the differences is the spatial resolution of the reanalyses.

There are a few remarks concerning table 3. The highest mean number of the cyclones belongs to ERA-Interim reanalysis in all domains, while the lowest mean number of cyclones is reported by 20cR2 reanalysis. South cyclones have the best similarity among the counts for all three reanalyses. The highest variability among the reanalyses was observed for the West cyclones within each of three domains.

Separately, we assessed deep cyclones that were defined as deep when SLP in the cyclone centre dropped below 1000 hPa for at least one observation time. The same criterion for terrestrial extratropical cyclones was applied in several other studies (see, Gulev et al. 2001, Zhang et al. 2004, Sepp 2005). These strong cyclones have a potential to cause striking weather contrasts. The difference between the total numbers of all cyclones and those with SLP < 1000 hPa range from 10 to 30% for Scandinavian, North and West cyclones and for South cyclones reaches 50–60%.

When evaluating the dynamics in the numbers of deep cyclones in three reanalyses, we found significant changes only in the first and second (expansive) domains. The reason for this could be that the expansive domains incorporate...
larger numbers of cyclones, which makes statistical estimates less noisy and more statistically significant. Another possible explanation could be that the atmospheric circulation changes during the past several decades (if any) were mostly large-scale and could not be noticed in a small (third) domain shown in figure 1.

We examined long-term tendencies in the cyclone trajectories of different origin to determine those of them which could correspond to climatic changes in Belarus. Evaluation of the dynamics of Scandinavian and West cyclones showed no systematic tendencies in the post-World War II period over our study domains. Being focused in this study on long-term multi-decadal changes, we did not consider these types of cyclones further.

The analysis of the dynamics of North cyclones (as well as of the sub-type of West cyclones passing close to the northern border of Belarus) shows noticeable tendencies of increase of cyclone numbers per winter season in the first and second domains respectively (according to MK test at the 0.01 and 0.05 levels). This increase in the number of North cyclones serves as evidence of the northward shift of the Atlantic cyclones (see, figure 4 that shows the changes of the North and South cyclone numbers in the first domain). For the past 60 years, we found statistically significant trends in both first and second domains when employed data of NCEP/NCAR and 20cR2 Reanalyses (according to LSM the linear trends are 0.2(10 yr)$^{-1}$ or 1.5 per study period and 0.15 (10 yr)$^{-1}$ or 1 cyclone per study period respectively).

The dynamics of the South cyclones (see, figure 4 for the first domain) show significant decrease in their numbers. According to the MK test, the trends (reduction of the South cyclone numbers) are statistically significant for the NCEP/NCAR and 20cR2 reanalyses (at the 0.05 level) in the first domain. The linear trends according to LSM are 0.5(10 yr)$^{-1}$ or 3 cyclones per study period for NCEP and 0.4(10 yr)$^{-1}$ or 2.4 cyclones per study period for 20cR2 Reanalyses respectively. Results for other domains for South cyclones were insignificant.

South cyclones bring to Belarus heavy precipitation (in winter, frequently in the frozen form) leading to a higher amount of snow on the ground and contributing to spring floods. The decrease in the number of South cyclones corresponds with observed decrease in the strength of spring floods in Belarus (Danilovich and Trofimova 2007).

When analysing the cyclone trajectories, we were interested in the long-term dynamics of their number for different cyclone types as well as in the changes of minimal SLP in the cyclone centres. The long-term tendency of minimal SLP values in the winter cyclones shows a net change of 3 hPa for the NCEP/NCAR reanalysis, being statistically significant at the 0.05 level. However, the data of ERA-Interim and 20cR2 reanalyses do not support a notion about systematic changes in SLP (figure 5).

Sampling cyclones according to their direction is highly disputed. We applied the scheme of cyclone movement by Krichak (1956) and analysing weather maps of distribution of the trajectory of cyclones during winter for the period of 63 years from 1949 to 2012. Krichak wrote in detail about typical distribution of these cyclones. Singling out some West cyclones (we rename them as North cyclones) is the result of grouping of isolated sub-group of cyclones, which was traced on the map and was formed as a separate group. It is clearly seen, that these cyclones do not differ from West ones according to their climatic characteristics; but their trajectory, passing Belarus northward of its North borders, motivated us to analyse this sub-group separately. The finding of an increase in the number of North cyclones in the absence of changes in the number of West cyclones, confirms the legitimacy of our choice.

3.2. Change in the precipitation regime and its connection with the spring floods (fresht) formation

The scale of spring floods in Belarus is affected by numerous factors amongst which the most important are: precipitation (during the snowmelt), snow water accumulation prior to fresht, depth of frozen soil, soil wetness since the previous autumn, the presence of ice crust before flooding, the
Cyclones, passing Belarus or its outskirts, bring there precipitation and change in temperature, especially during winter. Quantification of winter cyclone characteristics allows us to evaluate (to some extent) formation of main freshet factors, i.e. to connect quantitative characteristics of cyclones with meteorological parameters.

We assessed the profound effect of North and South cyclones (because of their trends being statistically significant) on the streamflow formation during winter and maximum streamflow during spring floods. To do that, we conducted a factor analysis using monthly precipitation totals and mean surface air temperatures during winter, the winter minimum streamflow, the spring maximum streamflow, and the data on the reoccurrence of North and South cyclones.

We used factor analysis (Brown 2006) to describe variability among our observed, correlated variables in order to reveal a potentially lower number of unobserved variables (factors). The goal of factor analysis is to choose the fitting hyperplane (a linear combination of observed variables) such that the reduced correlation matrix reproduces its correlation matrix as nearly as possible, except for the diagonal elements of the correlation matrix which are known to have unit value. In other words, the goal is to reproduce as accurately as possible the cross-correlations in the data. Thus the variables strongly correlated among themselves are ascribed as ‘one factor’. We searched for such complex factors which could explain connection between our six variables applying rotation by the Varimax method with Kaiser normalization. Factor values of the rotated matrix are presented in the component plots in figure 6 for four representative river sub-basins with terminating streamflow gauges at Polotsk (for Zapadnaya Dvina), Grodno (for Neman), Mogilev (for Dnepr), and Mozyr’ (for Pripyat’).

The figure shows two groups of factors that are closely linked together. The first group of factors are: North cyclones, surface air temperature, and winter minimum streamflow. The second group of factors consist of South cyclones, winter precipitation, and maximum streamflow of spring floods.

According to the analysis, the first group of factors empirically explains the influence of North cyclones on the winter temperature regime in the river basins: moving in zonal direction from West to East these cyclones block cold air masses from the high latitudes which results in higher temperatures in the region. These mild winters promote thaws and snowmelt increasing winter streamflow.

The second factor group allows a conclusion that South cyclones influence the winter precipitation totals, which, in its turn, defines the depth of snow cover and water supply in snow before the freshet onset. These factors (thus the South cyclones number), control the maximum water flow during spring floods.

Pattern of long-term trends and net change of seasonal (winter) sums of precipitation over Belarus are shown in figure 7(A). Trend estimates show an increase in winter precipitation in the north and central part of the country as well as in a few regions in southwest and southeast of the country.

The highest values of net change were in the North, in Vitsebsk and Polotsk where mean total sums have increased by 70–90 mm. These increases are statistically significant at the 0.01 level according to the MK test statistics. On the West of the country, some decrease of winter precipitation (the net change from 5 to 15 mm per season) was not statistically significant. Maximum liquid water equivalent of precipitation and its duration in the winter season change in accordance with seasonal changes of the mean precipitation totals. Thus, increase in maximum daily precipitation amounts was registered in the northern, central, and some southern regions of the country (figure 7(B)). But values of the net change of maximal precipitation totals being small (within 1 to 5 mm range) remain statistically insignificant. The duration of precipitation also increased in the North and Centre of Belarus (by 60–80 h while their long-term mean values are 250–260 h). Over the rest of the country (especially in the South), a gradual decrease in precipitation durations was observed (figure 7(C)). But values of the net change of the duration precipitation showed insignificant results.

We found that precipitation increases in the northern Belarus. It is connected with the growing number of North cyclones, which block the Arctic air invasions and bring humid Atlantic air. The latter does not influence the Southern

![Figure 5. Time series and linear trends of average minimum sea level pressure in cyclone centres for winter season (DJF) according to NCEP/NCAR, Era-Interim and 20cR2 reanalyses in the first domain.](image-url)
half of the country. The absence of significant changes of winter precipitation in the South (which was expected due to the reduction of the number of South cyclones) can be explained by compensation related to precipitation brought by the increasing number of North cyclones. Analysis of SLP and the duration of life of cyclones did not show significant changes with time. As a result, the winter trends in maximum precipitation and the length of precipitation do not differ from the trends in seasonal precipitation totals.

Air temperature has increased and winter precipitation is closely connected with the snowpack volume before spring floods and with processes of winter accumulating and discharge of this snowpack (Melnik and Komarovskaya 2010 and 2011; figure 6). These connections explain why the change in precipitation triggers changes of formation of

Notations in the Figure: North - north cyclones, South – south cyclones per winter, Prec – winter precipitation, Temp – winter surface air temperature, Qwinter - discharges for winter low-water season, and Qmax - maximum discharges of spring floods

**Figure 6.** Component plots of factors in rotated space for four river basins within the territory of Belarus.

**Figure 7.** Spatial distribution of net change in the winter precipitation for the 1949–2010 period, mm (A), its daily maximum values, mm (B) and duration, hours (C). The hatched area in (A) outlines statistically significant values of change at the 0.05 level.
rivers’ discharge, i.e. the increase in low-water streamflow and consumption of the water supply accumulated in snowpack, influences the spring flow and thus reduces the recurrence of inundations in Belarus.

### 3.3. Spring freshet and winter streamflow and precipitation

There are strong connections between winter precipitation and spring streamflow. The hypothesis of our study is that high totals of winter precipitation cause considerable inflow of melt water later and predefine high freshets and possible the inundation. Inundation means that the water level in the river exceeds the safe line and water floods to the adjacent territories. The distribution of the inundation events on 4 main river basins is shown on figure 8. It shows the dynamics of the inundation frequency at different strength scales (outstanding — 3, large — 2, small — 1). The largest numbers of inundation events were registered in 1951, 1953, 1956, 1958, 1962–1968, 1970, 1979, 1994, 1996, 1999, 2004 and 2010.

The spread of the grades of high inundations (grades 3 and 2) were often observed in the first 10 years of the study period while in the other decades inundations of lower grades were mostly observed.

To understand why the quantity of inundation decreases, we estimated trends of minimum and maximum discharge during winter and spring, which are shown in figure 9. Figure 9(A) shows change of minimum streamflow (in winter), the greatest changes were found for Northwest where they varied from 1.4 to 2.4 litre s\(^{-1}\) km\(^{-2}\) (Zapadnaya Dvina River Basin). The lowest values of the winter minimum streamflow change were observed in the West part of the country in the Neman and partly in the Pripyat’ River Basins (from 0.2 to 1.0 litre s\(^{-1}\) km\(^{-2}\)). On the rest of Belarus values of the winter streamflow change were from 1.4 to 1.8 litre s\(^{-1}\) km\(^{-2}\).

Figure 9(B) shows a reduction of maximum streamflow over the entire Belarus, with the largest changes being characteristic for Northwest (Zapadnaya Dvina and Neman River Basin) and the Pripyat River Basin. The spread of grades of high freshet (grades 3 and 2) were often observed in the first 10 years of the study period while in the other decades inundations of lower grades were mostly observed.

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Basins) ranging from 18 to 32 litre s\(^{-1}\) km\(^{-2}\), Southwest (Zapadny Bug River Basin) and East (Sozh River Basin that is the Dnepr River sub-basin). But the changes in the easternmost regions were within the tolerable limits: from 12 to 35 litre s\(^{-1}\) km\(^{-2}\).

In the Zapadnaya Dvina River Basin the decreases are ranging from 15 to 18 litre s\(^{-1}\) km\(^{-2}\) with a tendency to be higher in the West. The lowest changes of spring freshet decrease were in the South and Central part of the country, mainly in the Pripyat’ River Basin, where the changes were between 4 and 18 litre s\(^{-1}\) km\(^{-2}\).

Decreases of streamflow in spring floods were statistically significant at Zapadnaya Dvina, Neman and Dnepr Rivers at the 0.01 level, while the changes in the Pripyat’ River Basin were insignificant.

The increase in the number of North cyclones influenced the positive precipitation trend in the North and partially in the centre of the country; the largest changes in the maximum flow levels in spring flood are also registered here. Further southward, the influence of cyclone trends goes down and becomes insignificant.

Redistribution of North and South cyclones caused changes in formation of rivers’ discharge during spring floods. The increased number of winter cyclones affected both the rise of level of low-water streamflow in winter and the exhaustion of the resources of water supply in snow before spring flood. Thus the decrease of the number of South cyclones which could potentially make up the stock of snowpack, led to a decrease of spring streamflow and the reduction of the number of strong inundations across Belarus.

4. Conclusions
1. The number of North and South cyclones has changed significantly for the first and second study domains. In the small study region (domain 3) we did not find significant changes in the cyclone frequency. It is proved by the data from 2 reanalysis (NCEP and 20cR2) with long time series 1949–2012.
2. Due to increase in the number of North cyclones, winter precipitation has risen in the northern half of Belarus. However, there is no clear tendency of the precipitation changes in the central and southern parts of the country. At the same time the number of South cyclones decreased with time and the frequency of days with snowstorms has decreased. This tendency caused the decreasing of the snow cover depth (Melnik and Komarovskaya 2010 and 2011).
3. Increase of the North cyclones frequency which blocked invasions of cold Arctic air masses and caused frequent thaws, and decrease in the frequency of South cyclones, which bring severe winter weather, caused an intra-annual distribution of the streamflow over most of Belarus—significant increase in winter and decrease in spring.
4. Intra-annual distribution of the streamflow caused growth in the frequency of winter floods and increase of values of minimal discharges during winter low-water due to higher air temperatures and additional inflow of melt water to the rivers. Low values or even absence of snow cover and ice on the rivers and grounds, low depth of ground freeze (see, Nekrasova 2004) exhaust the water supply before freshet making conditions for large floods less probable. This tendency is supported by the decreasing trends of South cyclones frequencies and decreasing snowfall during the last decades.
5. The pattern of change in streamflow corresponds to the geography of cyclone frequencies trends. North cyclones mostly influenced the precipitation and winter and spring streamflow in the northern part of the country (where the values of net streamflow change are high and statistically significant). There are no similar tendencies in the central and southern parts of Belarus. It could be explained by a synchronous decrease in the South cyclones frequency.
6. The intra-annual distribution of the streamflow and, especially, a decrease of its spring portion caused the reduction of extreme inundation of adjacent territories in the river valleys of Belarus during freshet.

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