Снежный покров и снежные лавины

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Impact of snowfall measurement deficiencies on quantification of precipitation and its trends over Northern Eurasia

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Влияние погрешности в измерениях снегопадов на суммы атмосферных осадков и их тренды по Северной Евразии

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Однородность временных рядов осадков, Северная Евразия, смещение в измерениях осадков, твёрдые атмосферные осадки, тренды.

Instead of «ground truth» precipitation, rain gauges at meteorological stations estimate a function of several variables. In addition to precipitation, these variables include temperature, wind, humidity, gauge type, state of the gauge exposure, and observational practices. Their impact and changes hamper our efforts to estimate precipitation changes alone. For example, wind-induced negative biases for snowfall measurements are higher than for other precipitation types and a redistribution of these types during regional warming can cause an artificial increase in measured precipitation. In such conditions, the only way to properly estimate actual climatic changes of precipitation would be a use of precipitation time series that are corrected for all known systematic biases. Methodology of such corrections has been developed and recently implemented for Northern Eurasia for the past 50+ years (up to 2010). With the focus on Russia, we assess differences that emerge when officially reported precipitation in the cold season is compared to corrected precipitation time series at the same network. It is shown that conclusions about trend patterns over the country are quite different when all sources of inhomogeneity of precipitation time series are removed and impact of all factors unrelated to the precipitation process are accounted for. In particular, we do not see statistically significant increases of the cold season precipitation over most of the Russian Federation and in Arctic Asia it significantly decreases.

Introduction

In all scenarios of the future climate changes associated with anthropogenic greenhouse warming, contemporary climate models project an increase in the cold season precipitation in high latitudes [29, 30]. This increase is associated with (a) the Arctic sea ice retreat/thinning and thus the availability of additional source of water vapor for the polar atmosphere and (b) a general tropospheric warming (strongest in the cold season in the high latitudes) that permits a higher water vapor holding by the atmosphere. Our confidence in these model scenarios increases when climatologies and trends are supported by *in situ* precipitation data. This raises a credibility issue for the precipitation observations that are extremely difficult to measure, especially for the solid form of precipitation [23, 31]. Recently a suite of algorithms was developed in the Voeikov Main Geophysical Observatory (VMGO) and implemented independently in Russia and the United States that allows accounting for all known measurement rain gauge biases over the former USSR [3–6, 17, 35]. In this paper, we shall compare reported cold season precipitation observations to those delivered by VMGO procedures and assess the differences in climatology and trends when reported data are used instead of bias-corrected precipitation.

Approach

We shall focus on two major types of snow events that generate the largest confusion in assessments of precipitation changes in high latitudes.

The first type of snow event is that falling in the shoulder seasons when surface air temperature is not far from 0 °C. Frequently, these are intense storms substantially contributing to the cold season precipitation totals. With regional warming in the same months, the composition of precipitation from these storms may change from more frequent frozen forms (snowfall) to more liquid or mixed forms (rainfall, sleet). The ability of all contemporary rain gauges to catch the last two forms of precipitation is much better than for snowfall and, therefore, they report increasing trends in *observed* precipitation totals that are artificial, being a function of earlier (in spring) or later (in autumn) transitions between different precipitation forms. This phenomenon was first reported for northern Norway [22] and we shall quantify it for the entire Russia up to 2010.

The second type of snow event is that falling during storms accompanied by strong winds, especially those causing flurries and blowing snow. Rain gauge measurements in these events are compromised in two ways. First, strong winds reduce significantly the snow amount inside the gauge that can report as low as 20–30% of the «ground truth» precipitation. Second, when strong winds cause snow to blow above the gauge orifice, gauges can catch false precipitation. Contemporary gauge constructions prevent snow from leaving its bucket and measurement overcatch occurs that may significantly overestimate the «ground truth» precipitation totals over open terrain of tundra, steppe, and in the vicinity of the airports (where most of modern meteorological stations reside). The VMGO technique accounts for these events (although with understandable random errors). However, when climatic changes include the changes in the near surface wind speed (cf., [7, 12, 14, 25]), systematic temporal biases are introduced to the *observed* precipitation measurements in the middle of the cold season. At that time of the year the relative biases (in percent of ground truth) in the observed precipitation are especially high.

Data

In this study, we employ two data sets, each of which includes observed and bias-corrected precipitation for Northern Eurasia. The first data set includes daily observations of 2095 stations [34, 35] for the period of observations up to 2000 (Russia) and up to 1991 (other countries of the former Soviet Union). The second data set includes daily and monthly precipitation data of 457 stations of the Russian Federation for the 1936–2010 period [41]. In both data sets the original observations were received from the World Data Center B for Hydrometeorology at Obninsk, Russia. The first data set has not been updated to present. Therefore, below we are using it only in climatological assessments. It has, however, the advantage of a larger spatial data extent (includes daily precipitation data for other 14 Newly Independent States prior to 1991) and its network for the Russian Federation is denser than the currently available stations in the second network [19, 41]. It is worthwhile to mention that the reduction in the former USSR meteorological network began earlier than in the 1990s, and in the peak of the precipitation network density in the USSR, climatologists had access to the data of more than 11,000 rain gauges (cf., [13, 15]).

Another important difference between NCDC and VMGO data sets is that the former archive has a separate raw daily precipitation observations, P_o, that have never been corrected while the latter archive has so-called reported daily observations, P_{o1966}, that incorporate rough «wetting» corrections since 1966 up to date (cf., [37]). These «wetting» corrections were supposed to account for moisture left unaccounted on the gauge funnel and bucket walls during the measuring process. In 1966, observers were instructed to add 0.2 mm to each non-zero precipitation measurement and report the total as new «observed» totals. Since January 1967, the instruction for frozen precipitation measurements was changed again and the wetting correction for them was reduced to +0.1 mm. Contemporary advance correction methods employ variable wetting corrections and, therefore, require removal of old wetting corrections (cf., [4]). P_{o1966} can be easily converted into P_o in the sub-daily time series. However, for the daily totals this conversion requires additional assumptions (cf., [24]).

Bias corrections of measured precipitation and their temporal changes

The bias-correction algorithm is thoroughly described in [3, 6, 10, 17]. Therefore, below we provide only a few of its formulae and a brief description of the reasons why these corrections are changing with time. Their absence in the observed data introduces artificial time-dependent inhomogeneities that overlay upon the ongoing climatic changes in the hydrological cycle of Northern Eurasia and may hide and/or exaggerate them misleading the users of this information.

Bias-corrected precipitation values, P, can be generated from observed P_o for each synoptic period of observation (currently, half day totals for most of the RF) using the following formula:

$$P = K(P_o + P_{add} - P_{blow}), \qquad (1)$$

where K, wind correction factor, is a function of precipitation type (solid, frozen, or mixed), near-surface air density, and wind speed at the gauge orifice during the period of precipitation; the last depends upon the measured wind speed (in Northern Eurasia it is usually measured, at 10 m

above the ground), the gauge exposure to the wind movement, and of the gauge aerodynamic properties (including the wind shield type). In Northern Eurasia, K values vary in the range from 1 to 2.5. Below we present the formula for K calculation borrowed from [3, 17]:
the coefficient K is calculated using the formula

$$K = 1 + A_0\mu^2U_h^2, \qquad (2)$$

where A_0 is a gauge-specific empirical dimensionless parameter, depending on the gauge aerodynamic features and equilibrium velocity of the falling precipitation particles (the values of A_0 for different types of precipitation and different air temperatures varied from 0.004 for rain and drizzle with temperatures above 2 °C to 0.033 for snow); μ is a coefficient of transfer from air density under the standard atmospheric conditions to the density under the actual conditions; and U_h is the wind speed (m s^{-1}) at the height of the gauge orifice during precipitation. The coefficient μ is given by

$$\mu = 0.273P_a^2/[(273 + t_a)(Pa + 0.4e_a)], \qquad (3)$$

where P_a is the atmospheric pressure (hPa) at the station; t_a is the air temperature (°C); and e_a is the partial pressure (hPa) of water vapor.

Wind speed U_h at the gauge orifice height h (m) during precipitation is obtained from

$$U_h = U_H \times m(A)\ln[(h - h_s)/z_0]/\ln[(H - h_s)/z_0], \qquad (4)$$

where U_H is the wind speed (m s^{-1}) at the height of the standard wind-measuring device during precipitation; $m(A)$ is a coefficient characterizing the distortion of the logarithmic wind profile due to various obstacles surrounding the precipitation gauge; H is the height (m) of the wind measuring device; h_s is the snow-cover depth (m) at the station; z_0 is the roughness parameter of the land surface around the gauge (for continuous snow cover $z_0 = 0.01$ m; for the grass and patchy landscape, when snow covers less than a half of surroundings, $z_0 = 0.03$ m).

The coefficient $m(A)$ is [23]

$$m(A) = 1 - 0.024ά(A), \qquad (5)$$

where $ά(A)$ is the vertical angle from the rain gauge orifice to the top of the highest of the obstacles located less than 300 m from the gauge in the wind direction (A, degree).

In Northern Eurasia a volumetric precipitation measurement technique is employed when the rain gauge bucket content is emptied into the gauge measuring glass. Accordingly, correction P_{add} is a cumulative correction for precipitation that did not reach this glass. It includes precipitation that evaporated from the gauge before the cessation, was left on the gauge funnel and bucket walls, and was reported but was too small to be measurable (traces). This correction depends upon the number of measurements per day, atmospheric humidity, temperature, gauge type and precipitation type. Its relative values (in % of P) vary from −5% to +20%. P_{blow} is a cumulative correction for precipitation that was blown up into the air from the ground during blowing snow events and blizzards that ended up in the gauges and stayed there (being caught) up to the cessation. Blowing snow and blizzard events are widespread over Northern Eurasia in the cold season [35, 36] but only in the windy open sites do they play an important role and their absence can double the «observed» cold season precipitation [3, 4, 17].

Under very strong winds, blowing snow and blizzards become less distinct. Moreover, during a strong blizzard, it is practically impossible to determine whether the snow falls from the clouds or is raised from the surface of the snow cover by the wind, or whether both process are occurring simultaneously. Therefore, for strong snow storms with $U_H > 10$ m s^{-1} and the presence of snow on the ground the correcting algorithm (1) through (5) is amended with a special case formula [3, 17]:

$$P = Jp \times \tau_p, \qquad (6)$$

where Jp is a long-term mean monthly precipitation intensity calculated at a given station for wind speeds lower than 10 m s^{-1} and τ_p is the observed duration of blizzard precipitation during a given time interval. In these cases, precipitation measured by rain gauge is not taken into account.

Keeping in mind, that P_o and P_{o1966} are not observed during each synoptic observing time (that is now every three hours and prior to 1966 four times per day, while at present precipitation totals are reported twice a day over most of the Russian Federation), the variables that were observed more frequently (wind, temperature, humidity, atmospheric pressure) in the above formulae are averaged over the interval between precipitation observations using Simpson formula. This brief description indicates that while all processes that cause biases in precipitation measurements are well-known and studied in hundreds of papers (cf., [9, 10, 23, 37]), the actual implementation of bias-correction routines is extremely laborious. It requires for each gauge site a near-complete set of synoptic information, physical description of the meteorological ground and its neighborhood, and information about the history of observational practice and instrumentation. Frequently, in operational practice this information is not available and bias-corrections are replaced by simplified routines or are not used at all.

Since the early 1950s, there was only one major type of Russian precipitation gauge equipped with Tretiakov wind shield [15, 23]. The rain gauge orifices are elevated 2 meters above the ground. Therefore, while wind shields are specifically designed to reduce the wind impact on the gauge catch, wind-induced turbulence around the gauge orifice prevents entry to a fraction of light raindrops (drizzle) and to a larger fraction of snowflakes through the measuring gauge funnel. This turbulence causes a «wind undercatch». Thus, changes in wind speed around the gauge orifice (natural, or due to changes of the wind exposure of the gauge) may create inhomogeneity of the measurements unrelated to the precipitation process. This inhomogeneity in the cold season can be very high at the stations well exposed to the wind. Additionally, the homogeneity of precipitation measurements is affected by a necessity to introduce additive corrections (P_{add}) to account for wetting and evaporation and for trace precipitation handling, each of which in turn depends upon precipitation type, atmospheric humidity, and the number of measurements per day. These corrections were changed with time. Prior to 1966, no additive corrections were introduced to the observations; after 1966 mentioned above «wetting» corrections were inserted into each measurement. The number of precipitation measurements per day changed in 1936 (from one per day to two per day), in 1966 (from two per day to four per day), and again in 1984 back to two per day over most of the former USSR except for the second time zone where it has remained four per day (most of European Russia belongs to this time zone). Finally, during the blowing snow events in open locations with strong winds (coastal areas, tundra and steppe zones), gauges can catch (and keep) the snow that was blown from the ground (instead of the skies). This «overcatch» (P_{blow}) must be accounted for and removed from observations too. With changes in temperature and wind at individual meteorological stations, P_{blow} values also begin to change.

In summary (this will be quantified below), reported precipitation over Northern Eurasia has biases and these biases have been changing with time, season, observation routines, and weather variables other than precipitation itself. These biases are sufficiently large in the cold and shoulder seasons when they can reach several hundred percent. Therefore, (*a*) if we want to document real changes in the water cycle over the high- and mid-latitudes of the continents (e.g., over Northern Eurasia), we must correct precipitation observations for biases and (*b*) if the bias corrections are not implemented and the observed or (that is even worse) reported observations are used (e.g., are delivered via the WMO Global Communication Network), the derived water budget products can mislead hydrologists, water managers, and other scholars who use contaminated information about precipitation and its changes.

Results

We analyzed individual station data and mapped the output of these analyses. Additionally, we generalized our findings within specific regions. Two types of the regions were used. For the former USSR, we employed a formal partition of its territory into the WMO regions as shown in Fig. 1, *a*. For the Russian Federation, we used subregions (see Fig. 1, *b*) which resemble climatic regions first introduced by Alisov [1] and are currently used in operational and climatological practices of the Russian Hydrometeorological Service (cf., [11]). The summer season (June–August) precipitation is beyond the scope of this paper and is not considered here. Most of our analyses are focused on two shoulder seasons in spring (April–May) and autumn (September–October) and in the mid-winter (January–February). In these seasons, we anticipate significant temporal changes in bias-corrections with the ongoing climatic change.

Climatology. Fig. 2 shows long-term mean values of precipitation biases (absolute values and in percent of *P*) for three periods within the cold and transitional seasons over the Russian Federation during the 1958–2010 period. While the absolute values of these biases in Siberia are relatively small due to low monthly precipitation, the same biases are well above 20% nationwide in the mid-winter and north of 60°N in the late spring (Table 1). In mid-winter, we found some windy places (mostly along the west Arctic and Pacific coasts), where P_o is higher than *P*. Here blowing snow events are frequent and infill the gauges with false precipitation that is well above all other (negative) biases. In the upper two panels of Fig. 3 we further illustrate this phenomenon for regionally averaged monthly precipitation. Here for the Russian Arctic north of 70°N and west of 110°E (WMO Region 20 in Fig. 1, *a*), we present the entire seasonal cycle of *P*, P_o, and intermediately corrected precipitation (introduced by Groisman and Rankova [24] that did not account for wind and blowing snow events but secured the time series homogeneity related to P_{add} that was destroyed by introduction into observed precipitation P_o wetting corrections converting it into P_{o1966}). The left top panel of Fig. 3 shows that in the high Western Arctic P_o values remain higher that *P* during the first three windy months of the year but thereafter became much less than *P* (cf., in October, when precipitation here is already in the frozen form but blowing snow events are still infrequent, the ratio P/P_o is about 1.6). As a contrast, the right top panel of Fig. 3 shows the seasonal cycle of the same precipitation characteristics for Central Kazakhstan, where blowing snow events are less frequent and the impact of the wind-induced biases in precipitation corrections prevails.

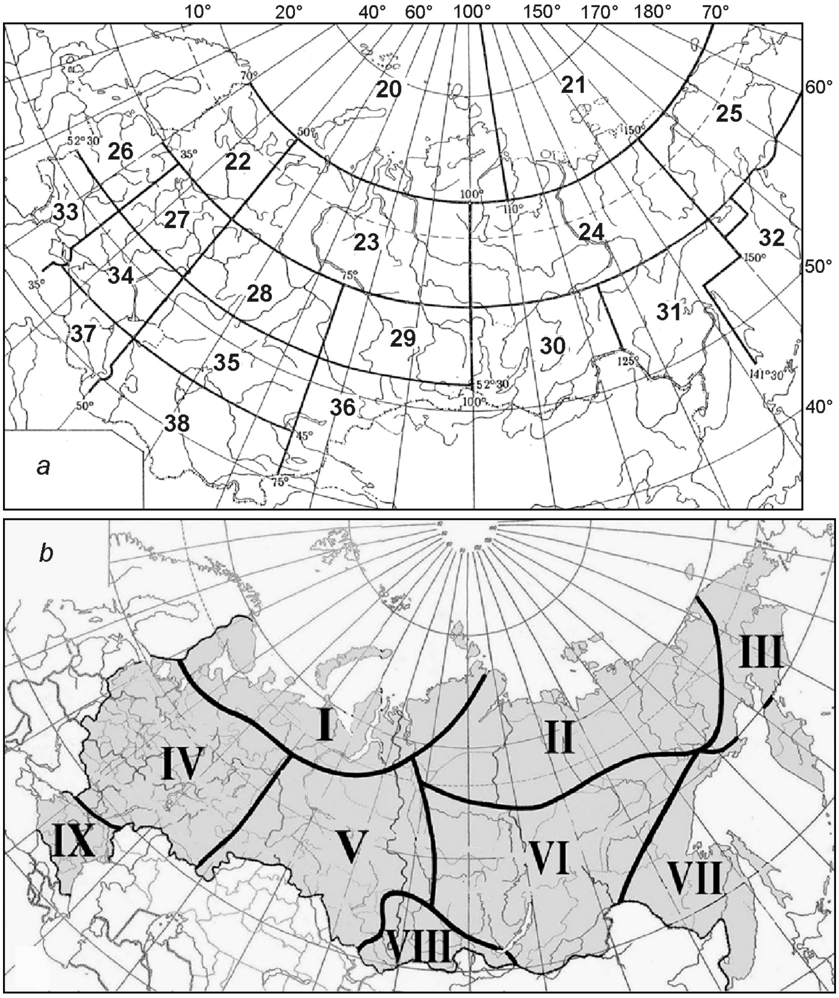

Fig. 1. (*a*) First two-digits allocation for the WMO station IDs over the former Soviet Union and (*b*) Nine climatological regions used by the Russian Hydrometeorological Service for the current National Climate Change Assessment [14]

Рис. 1. Расположение регионов СССР, выделенных согласно первым двум цифрам пятизначного кода ВМО (*а*), и девяти климатологических регионов, выделяемых Гидрометеослужбой России для докладов о современных изменениях климата по стране (*б*) [14]

The bottom panel in Fig. 3 shows the dynamics of precipitation corrections that we need to apply to reported precipitation (P_{o1966}) to restore ground truth precipitation, P, over the central part of European Russia in mid-winter and in late spring. This Fig. as well as our estimates for the warm season (June through August, not shown here) indicate that reported precipitation, P_{o1966}, are highly inhomogeneous time series all over the country throughout the entire seasonal cycle. The jump wise reduction of biases after 1966 does not eliminate them and the further reduction of these biases with time (especially prominent in mid-winter) does not guaranty that after 1966 we can consider P_{o1966} as a variable that reports changes in precipitation alone instead of changes in some variable function of precipitation, temperature, humidity, wind speed, and environmental changes in the vicinity of observational sites. Generally, in the cold season, various biases associated with strong winds (K, P_{blow}) dominate precipitation correction values, while P_{add} dominates in the warm season. Even for the annual precipitation totals, these corrections maintain two-digit values (in % of P_o) and in the coastal regions of the Asian part of Russia, the long-term mean corrections to measured annual precipitation are on the order of 30% (Fig. 4).

Changes in the shoulder and the mid-winter seasons. Northern Eurasia (north of 40°N, or north of 60°N) remains the region of the highest global warming for the period of large-scale instrumental observations (since circa 1880s; [27]). Since the late 1950s, the rates of warming in Northern Eurasia more than doubled compared to the entire period of instrumental observations (Fig. 5) being the strongest during the cold season, particularly in spring where the dates of the spring onset (e.g., expressed by the date of stable transition of the surface air temperature across 0 °C or by the date of the last frost) shifted by a week or two during the past five decades [16, 20, 21]). We selected the past 55 years for comparison of changes in precipitation for two reasons: this is a period of steady and strong warming in the region where we want to document the impact of this warming on the precipitation bias-corrections dy-

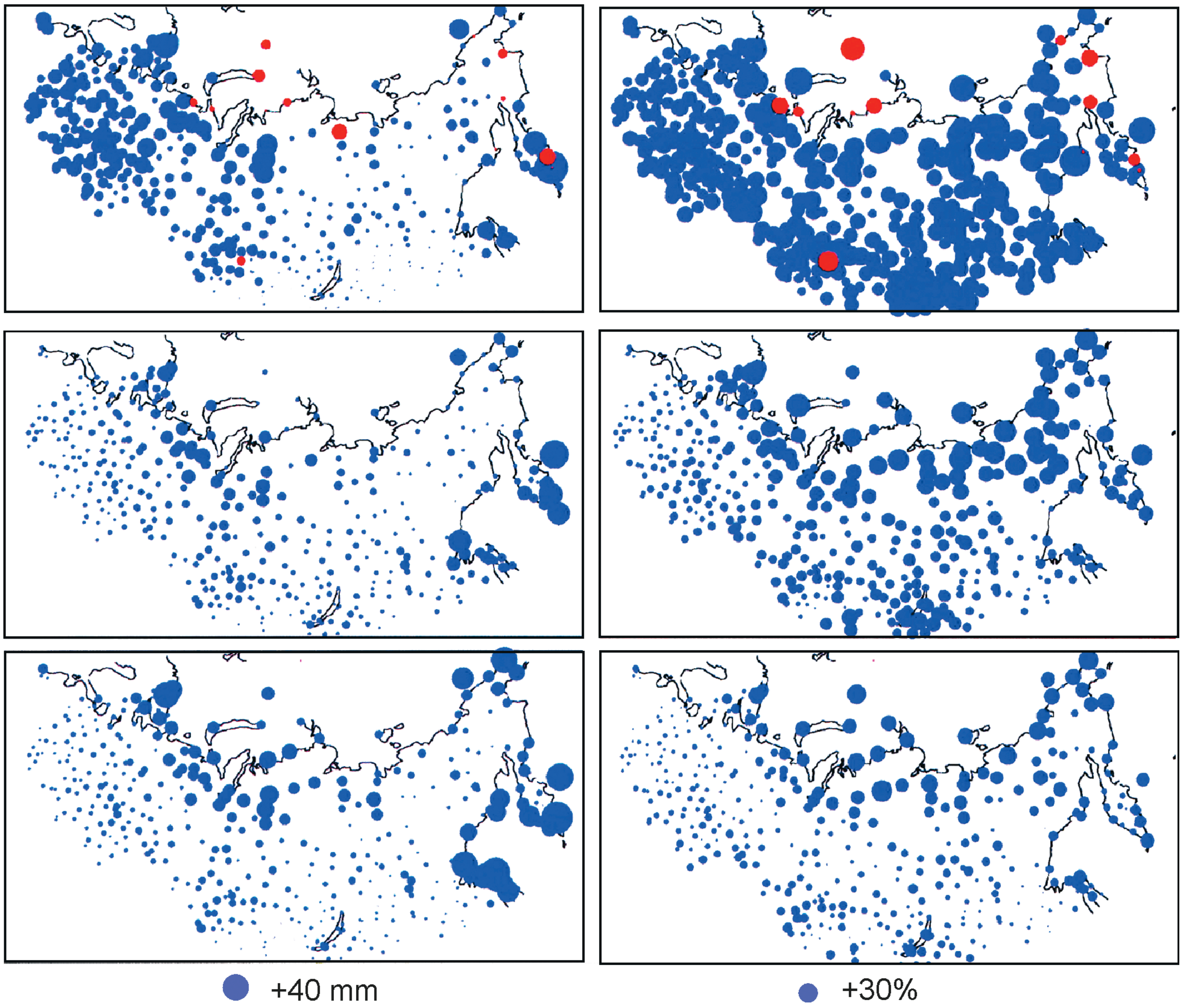

Fig. 2. Mean differences of corrected and reported precipitation totals ($P - P_{o1966}$) during the two-month-long periods of the seasonal cycle:
January–February (top line of the panel), April–May (second line of the panel), and September–October (bottom line of the panel) expressed in mm (left column) and percent of the long-term mean corrected precipitation, *P*, (right column). The diameters of the dots are proportional to the difference values shown in each plot. Positive differences (blue color) dominate over the negative differences (red; presented only in extremely windy areas in mid-winter with strong wind overcatch biases)

Рис. 2. Средние разности между исправленными и официальными суммами осадков ($P - P_{o1966}$) за три двухмесячных периода в сезонном цикле:
январь–февраль (верхняя линия карт), апрель–май (средняя линия карт), сентябрь–октябрь (нижняя линия карт), выраженные в мм (левый столбец карт) и в процентах от средних многолетних значений исправленных осадков, *P*, (правый столбец карт). Диаметры точек на картах пропорциональны значениям разностей. Число положительных разностей (голубой цвет) значительно превышает число отрицательных разностей (красный цвет, который присутствует только в середине зимы в районах с экстремально сильными ветрами, где наблюдаются сильные метелевые искажения (переоценка) измеренных полей осадков)

namics, and because since the late 1950s in the former USSR more metadata and supplementary synoptic and snow information have been archived that are required for proper implementation of precipitation bias-correction routines. This dynamics should be assessed for unchanging instrumentation. Tretiakov rain gauge has become a single rain gauge type employed by the regional meteorological network after mid-1950s and this was the other argument for us to select 1958 as a starting year in our analyses.

First, we partitioned the last 53 years into two nearly-equal time intervals, 1958–1984 and 1985–2010, and compared the mean bias-corrections ($P - P_{o1966}$) between these two periods. Fig. 6 and

*Table 1. Me*an regional corrections ($P - P_{o1966}$) during the 1958–2010 period for the two month-long intervals within the cold part of the seasonal cycle area-averaged over nine climatic regions shown in Fig. 1, *b* and presented in percent of *P*. Differences of regional corrections ($P - P_{o1966}$) between 1985–2010 and 1958–1984 periods are shown in parentheses.

Region	January–February	April–May	September–October
I – West Arctic	19(−3.1)	19(−3.7)	13(−3.9)
II – Central Arctic	27(−8.8)	27(−6.6)	18(−4.6)
III – North Far East	8(−2.6)	20(−2.5)	17(−0.5)
IV – European Russia	20(−6.0)	9(−3.9)	6(−4.9)
V – West Siberia	26(−4.6)	14(−4.5)	10(−6.3)
VI – East Siberia	26(−6.4)	14(−5.3)	8(−3.9)
VII – South Far East	22(−3.9)	12(−5.3)	8(−5.4)
VIII – Altai and Sayany	19(−5.2)	11(−4.2)	7(−3.2)
IX – North Caucasus	16(−6.0)	7(−2.4)	6(−2.2)

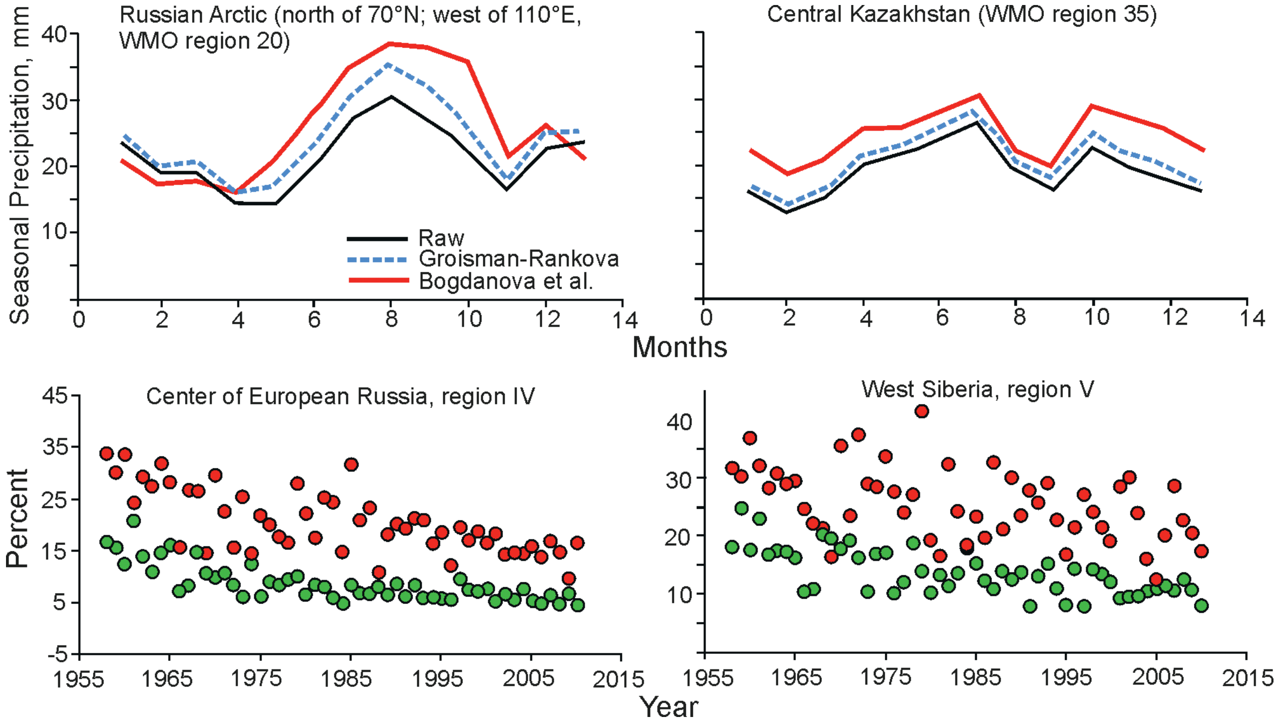

Fig. 3. ***Top***. The plots present arithmetic averages of raw monthly precipitation measurements, P_o, and their homogenized values constructed using the Groisman and Rankova [24] and Bogdanova et al. [3, 17] routines during the 1954–1990 period for (left) the Russian Arctic (WMO region 20) and (right) Central Kazakhstan (WMO region 35). Here we used the NCDC archive [35] that has nine long-term synoptic stations available for construction of the left plot and more than hundred stations available for the construction of the right plot. ***Bottom.*** Precipitation corrections that we have to introduce to P_{o1966} in order to convert them to *P*. Corrections are regionally averaged over the center of European Russia (region IV) and West Siberia (region V) and are presented for January–February (red dots) and April–May (green dots). Here we used the VMGO archive [41] where P_o is not readily available and is replaced by P_{o1966}

Рис. 3. ***Верхняя линия графиков***. Средний сезонный ход за период с 1954 по 1990 г. измеренных месячных сумм осадков, P_o, и их откорректированных на однородность временны́х рядов с использованием алгоритмов, предложенных в [3, 17, 24] и регионально осреднённых на графике слева по Российской Арктике (ВМО регион 20) и на графике справа по Центральному Казахстану (ВМО регион 35). При построении этих графиков были обработаны данные архива [35], в котором использовались девять длиннорядных синоптических станций для первого графика и более 100 таких станций для второго графика. ***Нижняя линия графиков.*** Поправки для получения *P* на основе P_{o1966}. Поправки арифметически осреднены по центру Европейской части России (регион IV) и Западной Сибири (регион V) и представлены для января–февраля (красные точки) и апреля–мая (зелёные точки). Для этих оценок использовался архив [41], где значения P_o отсутствуют, поэтому они были заменены на P_{o1966}

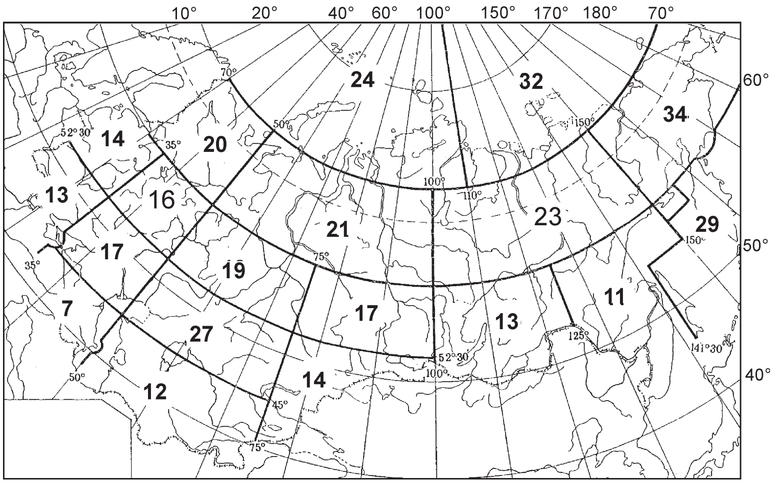

Fig. 4. Increase (%) in mean annual precipitation totals throughout the former USSR during the 1961–1990 period compared to measured precipitation, P_0 (data source: [35])

Рис. 4. Увеличение (%) средних годовых сумм атмосферных осадков по территории СССР с 1961 по 1990 г. по сравнению с измеренными осадками P_0 [35]

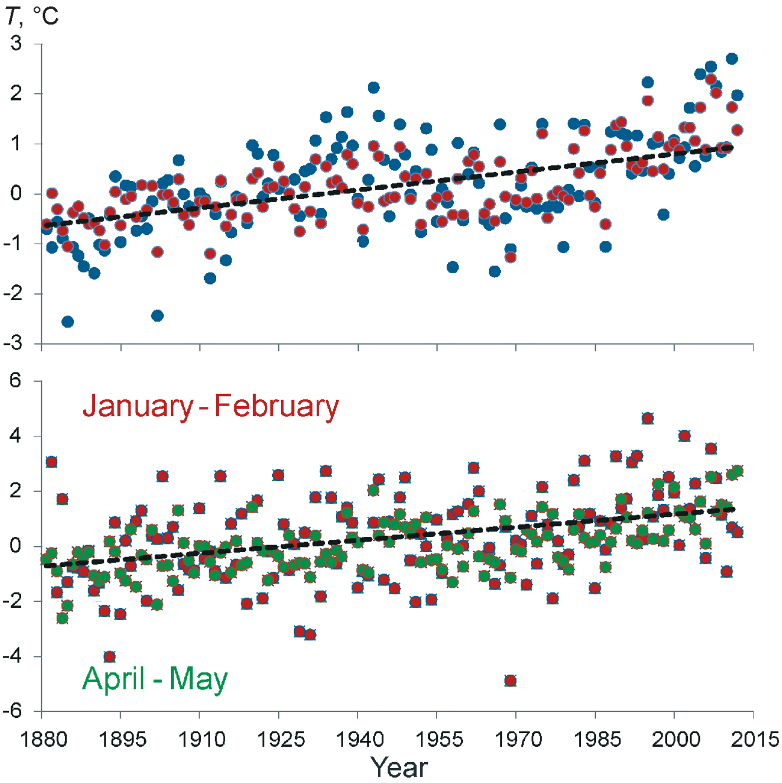

Fig. 5. ***Top***. Annual surface air temperature anomalies area averaged over Northern Eurasia north of 40°N (red dots) and north of 60°N (blue dots). Century-long linear trends for both these time series practically coincide being equal to 1.75 °C per 132 years. For the 1958–2012 period, the linear trend estimate for the «red» time series is equal to 1.75 °C per 55 years. ***Bottom***. Seasonal (two-monthly) surface air temperature anomalies area averaged over Northern Eurasia north of 40°N for mid-winter (red dots) and late spring (green dots). Century-long linear trends for both these time series also coincide being equal to 2.1 °C per 132 years; however, for the late spring season, linear trend is more visible and describes 36% of interannual variance of the time series (versus 13% for the mid-winter time series). The 1881–2012 period; Anomalies from the mean values for the 1951–1975 period. Source: Lugina et al. archive [32], updated

Рис. 5. ***Верхний график***. Аномалии средней годовой приземной температуры воздуха, пространственно осреднённой по Северной Евразии к северу от 40° с.ш. (красные точки) и к северу от 60° с.ш. (голубые точки). Линейные тренды этих двух рядов за период инструментальных наблюдений практически совпадают и равняются 1,75 °C за 132 года. За период с 1958 по 2012 г. оценка линейного тренда «красного» временнóго ряда равняется 1,75 °C за 55 лет. ***Нижний график***. Аномалии средней двухмесячной приземной температуры воздуха, пространственно осреднённой по Северной Евразии к северу от 40° с.ш. для середины зимы (красные точки) и поздней весны (зелёные точки). Линейные тренды этих двух рядов за период инструментальных наблюдений также совпадают и равны 2,1 °C за 132 года; заметим, что для поздней весны линейный тренд гораздо более виден, описывая 36% межгодовой изменчивости временнóго ряда (по сравнению с 13% для середины зимы). Период – с 1881 по 2012 г.; аномалии – от средних за период с 1951 по 1975 г. Источник – пополненный архив [32]

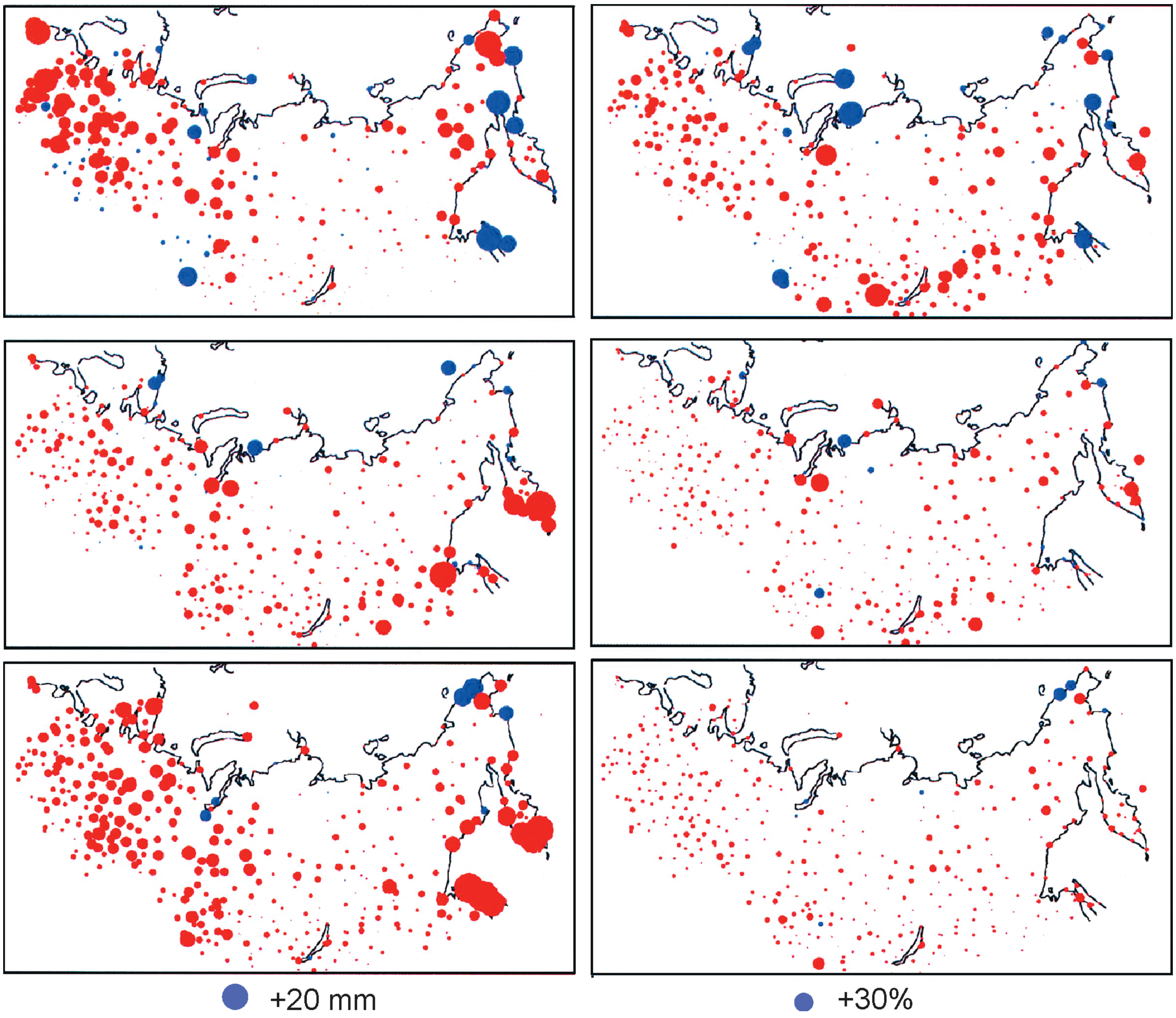

Fig. 6. Differences of corrections ($P - P_{o1966}$) between 1985–2010 and 1958–1984 periods during the two month-long periods of the seasonal cycle:

January–February (top line of the panel), April–May (second line of the panel), September–October (bottom line of the panel) expressed in mm (left column) and percent of the long-term mean corrected precipitation, P (right column). The diameters of the dots are proportional to the difference values shown in each plot. Negative differences (red color) dominate over the positive differences (blue; presented only in extremely windy areas in mid-winter with strong wind overcatch biases)

Рис. 6. Разность поправок ($P - P_{o1966}$) между 1985–2010 и 1958–1984 гг. в двухмесячных интервалах сезонного цикла:

январь–февраль (верхняя линия карт), апрель–май (средняя линия карт), сентябрь–октябрь (нижняя линия карт) в мм (левый столбец карт) и в процентах от средних многолетних значений исправленных осадков P (правый столбец карт). Диаметры точек на картах пропорциональны значениям разностей. Число отрицательных разностей (красный цвет) значительно превышает число положительных разностей (голубой цвет, который присутствует только в районах с экстремально сильными ветрами, где наблюдаются значительные метелевые искажения измеренных полей осадков)

Table 1 (in parentheses) show patterns (see Fig. 6) and regionally-averaged values of these differences in mm and in percent. Fig. 6 shows a conspicuous synchronous pattern of decrease of bias-corrections with time over nearly all territory of the Russian Federation in all three two-month intervals of the cold season. This decrease is a cumulative effect of increase in P_{o1966} due to introduction of «wetting» corrections (see Fig. 3, bottom panel), wind decrease over Northern Eurasia in the past decades [2, 7, 12] and warming. Weaker winds directly reduce the wind-induced bias and warmer temperatures increase chances that in transient seasons, precipitation will fall in liquid and mixed forms for which the rain gauge catch is much

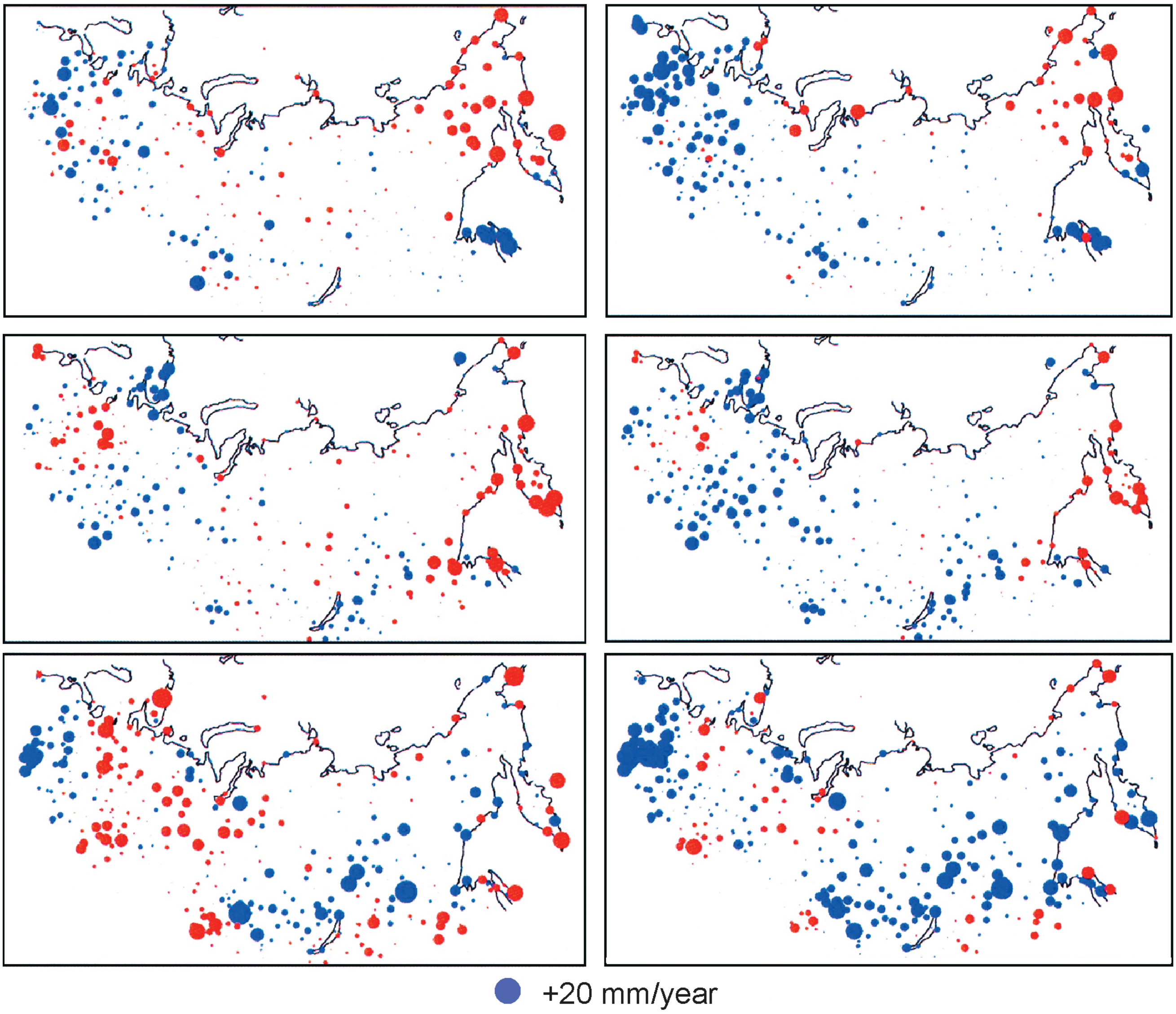

Fig. 7. Linear trends (mm yr^{-1}) of corrected (P, left column) and reported (P_{o1966}, right column) precipitation during the 1958–2010 period for the two month-long intervals within the cold part of the seasonal cycle:
January–February (top line of the panel), April–May (second line of the panel), and September–October (bottom line of the panel). The diameters of the dots are proportional to the trend values shown in each plot

Рис. 7. Линейные тренды (мм год$^{-1}$) откорректированных (P, левый столбец карт) и официальных (P_{o1966}, правый столбец карт) атмосферных осадков за период с 1958 по 2010 г. для трёх двухмесячных интервалов холодной части сезонного цикла:
январь–февраль (верхняя линия карт), апрель–май (средняя линия карт) и сентябрь–октябрь (нижняя линия карт). Диаметры точек на картах пропорциональны значениям трендов

better than for frozen form of precipitation. In Europe, the frequencies of days with thaw (when winter temperatures are close to zero and chances for rainfall are high) have also increased [26]. Finally, an observed mid-winter increase of bias corrections at several windy sites located along the Arctic and Pacific Oceans coasts also corresponds well to (can be explained by) weakening of the winter wind speeds. So mean wind speed during two winter months (January and February) precipitation Less frequent strong winds here mean fewer blowing snow events and less gauge overcatch and therefore fewer corrections for it. As a result, P-values became higher in these locations, because P_{blow} enter in Eq. 1 with negative sign.

The pattern shown in Fig. 6 was further generalized in Table 1, where we area-averaged our estimates and present them for each climatological region and part of the cold season. These regional estimates of $P - P_{o1966}$

Table 2. **Linear trend estimates of corrected precipitation (P) during the 1958–2010 period for the two month-long intervals within the cold part of the seasonal cycle. The trend estimates are area-averaged over nine climatic regions shown in Fig. 1, *b* and presented in mm per year (in the numerators) and in percent of P per year (in the denominators). Statistically significant estimates at the 0.1 and 0.05 levels are shown in bold italics and bold numbers respectively. Differences of linear trends of corrected (P) and reported (P_{o1966}) precipitation are shown in parentheses**

Region	January–February	April–May	September–October
I	0.00/−0.05(**−0.12/−0.19**)	**0.24/0.28(−0.10/−0.16)**	−0.04/−0.05(**−0.22/−0.19**)
II	**−0.24/−0.68(−0.11/−0.30)**	−0.07/−0.24(**−0.10/−0.30**)	0.02/0.02(**−0.13/−0.20**)
III	**−0.60/−0.95(**0.01/0.02)	**−0.25/*−0.41*(**−0.07/0.14)	−0.19/−0.02(***−0.11/***−0.04)
IV	0.06/0.07(**−0.23/−0.27**)	−0.01/0.00(**−0.15/−0.17**)	−0.01/0.01(**−0.23/−0.21**)
V	0.06/0.12(**−0.11/−0.18**)	0.13/0.17(**−0.14/−0.17**)	−0.20/−0.20(**−0.26/−0.26**)
VI	0.00/0.04(**−0.07/−0.28**)	0.07/0.14(**−0.12/−0.22**)	0.14/0.15(**−0.13/−0.17**)
VII	0.10/0.22(−0.05/**−0.10**)	**−0.39**/−0.39(**−0.24/−0.22**)	***−0.39/−0.24(***−**0.32/−0.18**)
VIII	−0.01/−0.08(**−0.06/−0.21**)	0.06/0.06(**−0.11/−0.16**)	0.09/0.11(**−0.11/−0.13**)
IX	−0.09/−0.12(**−0.29/−0.29**)	0.01/0.08(**−0.10/−0.09**)	**0.64/0.50(−0.09/−0.09)**

are more robust than individual station differences and clearly signal that during the entire cold season in the last decades, biases in precipitation measurements over the Russian Federation have been reduced. After 1966, warming and reduction of moderate wind speeds were the probable causes of this reduction. Reduction of the number of strong winter storm events with time during the 1979–2010 period that encompasses the last three decades analyzed in this paper (cf., Fig. 7 in [38]) could reduce P_{blow} along the oceanic coasts and thus make $P - P_{o1966}$ larger (cf., Fig. 6 and relatively low absolute values of these differences in Table 1 for Regions I and III). For example, at the Dixon Island station on the coast of the Kara Sea, U_H decreased by 6.5%/50 yrs and the number of U_H measurements exceeding 10 m s^{-1} has reduced by 20%/50 yrs. However, region-wide the negative sign of $P - P_{o1966}$ changes remains intact (see Table 1).

Precipitation trends in the shoulder and the midwinter seasons. Table 2 provides our estimates of the mean rates of changes in the cold season precipitation (for two month-long intervals within the cold part of the seasonal cycle) during the past 53 years (1958–2010 period). The estimates are based upon corrected precipitation only and are area averaged over the nine regions shown in Fig. 1, *b*. For the same 3 two-month long intervals during the 1958–2012 period, Northern Eurasian surface air temperatures have increased by 2.2 °C (55 yr.)$^{-1}$, 3.0 °C (55 yr.)$^{-1}$, and 1.9 °C (55 yr.)$^{-1}$ respectively for the region north of 40°N and by 1.8 °C (55 yr.)$^{-1}$, 3.0 °C (55 yr.)$^{-1}$, and 1.9 °C (55 yr.)$^{-1}$ respectively for the region north of 60°N. All these temperature changes have been statistically significant at the levels of 0.05 or above. On the contrary, the cold season precipitation trends are mostly statistically insignificant (Table 2). It is worthwhile to note the precipitation decreased across most of the Russian Far East in the second half of the cold season (Regions II and III) and the autumn (September–October) precipitation increased in North Caucasus (Region IX). Estimates of the autumn decrease of P over most of the Volga Basin, Urals, and West Siberia in the western half of Russia, shown in Fig. 7 have not exceeded the 0.1 statistical significance level.

From the previous section, we conclude that any systematic increase in the cold season precipitation reported by observed data over the Russian Federation is somewhat overestimated while systematic decrease (if it exists) is underestimated or even reversed due to systematic nationwide changes in precipitation corrections (see Fig. 6, Table 1). Furthermore, Table 1 shows that discrepancies between results based upon corrected and reported precipitation time series are substantial (up to 8.8% for the two multi-decadal intervals in the Central Russian Arctic). Therefore, the signs of differences between trend estimates in P and P_{o1966} presented in Fig. 7 and Table 2 (in parentheses) were expected beforehand. However, the strength of the signal contamination revealed by them was unprecedented. P_{o1966}-trend patterns report confidently the cold season precipitation increase over most of the Russian Federation except the Far East. At the same time, P-trends in Fig. 7 and Table 2 do not indicate systematic changes in the cold season precipitation totals over most of Russia except in the northeastern regions of the country where these totals decrease. This is a completely different picture of the ongoing cold season precipitation changes over most of Northern Eurasia.

Table 2 (columns in parentheses) shows regional trends in $P - P_{o1966}$ or (which is the same due to linearity of the trend estimation procedure) differences of linear trends between these two quantities. The most impressive feature of this Table is not the same sign of trends in $P - P_{o1966}$ (it was expected from Table 1), but a strong significance (frequently well above the 0.01 or even 0.001 levels) of these differences. For 6 months' cold season (November, December, and March were excluded from our analyses without particular reason in order to keep three 2-month intervals of the cold season apart), P totals report for the Central European Part of Russia (Region IV) an insignificant linear trend of +0.04 mm yr^{-1} (see Table 2) that is less by 0.61 mm yr^{-1} or by 32 mm per 53 years from one delivered by reported observations. Let us note that 32 mm in this Region represents 11% of the long-term mean corrected precipitation for these six months.

Discussion

If and when the observations change with time due to causes unrelated to the precipitation process, our ability to rely on uncorrected observations for assessments of the cold season precipitation changes wanes and without comprehensive bias corrections, *observed* frozen precipitation measurements are not able to report true tendencies in the rapidly changing environment of the high and mid-latitudes of the Northern Hemisphere. The above statement was tested for the Russian Federation for the past 5+ decades, where we use data of a well spatially-distributed network of stations with bias-corrected precipitation time series up to 2010. Since mid-1950s, the rain gauge type in this network has not been changed. While the observational practice at the network was changed twice (in 1966/67 and in 1984) by switching from two per day to four per day measurements and back to two per day measurements, its impact on raw uncorrected precipitation time series in the cold season (P_o) was not large [24]. This allowed Russian researchers to remove ill-conceived wetting adjustments from reported precipitation data and use P_o in climatological analyses (cf., [34]) or account for biases in a simplistic way replacing the conclusions about the absolute precipitation changes in mm with their relative changes in percent (cf., [24]). If the user has only P_{o1966}, he or she cannot use these approaches.

In the past 5+ decades in the cold season, over most of the Russian Federation very few significant precipitation changes were documented (see Table 2 and Fig. 7, left column[1]). However, these climatic changes and introduction of wetness adjustments to observations caused highly significant changes in corrections that we have to employ to secure homogenous time series of actual precipitation (see Table 2). This implies that without these corrections the raw precipitation observations, P_o, as well as observations that were adjusted for wetness losses since 1966 (P_{o1966}) over most of Northern Eurasia cannot be used to report precipitation trends over Russia. The trend estimates will be biased towards a fictitious increase of precipitation in the last decades, may have the wrong sign, and their statistical significance may be compromised. We checked this statement for the April–May season in Siberia. Siberia was the largest area in Russia where the First National Climate Change Assessment Report [14] found statistically significant increase in observed spring precipitation totals for the 1976–2006 period. The authors of the Report warned the readers about potential pitfalls associated with observation biases in their data. However, the dataset [41] was not yet ready five years ago and the Report authors had to use data that were uncorrected for systematic biases. Now, we can check the cost of that compromise using the longer time series over the same region (cf., middle line of panels in Fig. 7). For the 1958–2010 period, linear trend estimates of P_{o1966} area-averaged over West and East Siberia (V and VI regions respectively) are statistically significant at the 0.05 level or higher. In reality, Table 2 shows no discernable changes in P and statistically significant *negative* trends in precipitation corrections.

Bulygina et al. [18] began their analyses of changes in snow water equivalent over the Russian Federation since 1966. If one were to select using P_{o1966} since this year (or better since 1967), a major inhomogeneity cause in corrections to ground truth precipitation will be reduced. This «easement» has three major objections: (*a*) Bulygina et al. [18] had no choice because the pre-and past 1966 snow course observations were completely incompatible, which is not true for precipitation measurements; (*b*) the precipitation biases keep changing (decreasing) after 1966 for other reasons (cf., Fig. 3, bottom panel) and the shortening of the analyzed period will not help to avoid these changes; and finally (*c*) in the region with 120 years of history of large-scale precipitation observations (since circa 1891, cf., [8]) an ignorance of the first 75 years of precipitation observations would not allow unyielding conclusions about the variability range in this key (and undisputedly most societally-important) characteristic of contemporary and future climatic changes.

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[1] In the warm season (June through August) corrected precipitation has not changed either, except the Russian Pacific Arctic (Region III in Fig. 1, *b*) where P has steadily and statistically significant decreased with a mean rate of 5% per decade.

Conclusions

Eurasian climate has noticeably changed. Surface air temperatures increased by 2 to 3 °C (see Fig. 5), the frequency of intense cyclones across the Northern Hemisphere since 1979 has been reduced as well as the total number of winter cyclones over most of Russia north of 60°N [38]. Mean wind speed at the Russian meteorological stations has decreased [2, 7, 12, 14] and using our past experience, although acquired in another part of the northern extratropics [24], we infer that the wind speed during precipitation events, U_H, has also decreased. Apparently, these climatic changes did not yet cause significant changes in actual («ground truth») cold season precipitation over Northern Eurasia except the Asian Arctic.

Theoretical considerations (cf., [29, 39]) and empirical evidence based on analyses of P_{o1966} (see Fig. 7, right column) suggest that cold season precipitation at high latitudes has increased and will further increase with projected anthropogenic global warming. Now empirical evidence based on analyses of P (see Fig. 7, left column) shows no tendency towards more humid cold seasons in Northern Eurasia. Furthermore, the land surface water deficit in the warm season ($P - PET$; precipitation minus potential evapotranspiration) may decrease in mid-latitudes of the Northern Hemisphere leading to summer dryness which is predicted by some GCM experiments forced by increasing CO_2 concentration in the atmosphere (cf., [33, 40]). In the second half of the 20th century – early 21st century, this scenario for Northern Eurasia began to conform to observations [28]. In dry climates of Northern Eurasia, snow on the ground accumulated during the prolonged cold season provides an additional source for early summer soil moisture. If the «no trends» situation reported in Table 2 and left column of Fig. 7 remains intact in the future and the temperature increase will keep driving earlier spring onsets and earlier snowmelt, the water resources available for the summer season from the earlier months will decrease. This may further increase the severity of summer conditions in the dry years over Northern Eurasia.

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Влияние погрешности в измерениях снегопадов на суммы атмосферных осадков и их тренды по Северной Евразии

В статье анализируются результаты применения методики полной корректировки срочных осадков относительно станционных данных по осадкам бывшего СССР с приоритетом на территорию России, для которой временны́е ряды дополнены по 2010 г. Эти результаты сравниваются с измеренными показаниями осадкомеров на тех же станциях, что позволяет оценить различия в средних значениях (климатологии) и систематических изменениях (трендах) осадков по территории бывшего СССР (Российской Федерации).

Показано, что измеренные и откорректированные среднегодовые осадки для территории бывшего СССР различаются на 7–15% в южных районах СССР, на 15–20% на большей части России и на 25–35% в открытых ветрам степях Северного Казахстана и на побережье Северного Ледовитого и Тихого океанов, причём везде откорректированные годовые осадки выше измеренных. Несмотря на то, что в сезонном ходе зимние осадки (особенно в Сибири) невелики, относительные изменения между откорректированными и наблюдёнными зимними осадками на большей части территории Российской Федерации максимальны и могут достигать 100% на открытых ветру метеорологических площадках.

Показано, что заключения об изменениях осадков в холодный период года по России, сделанные на основе исправленных рядов атмосферных осадков, отличаются от выводов, базирующихся на анализе официально поступающих в мировую сеть метеорологических данных. Когда все источники неоднородности рядов устранены и учтено влияние всех факторов, прямо не связанных с процессом осадкообразования, статистически значимый рост сумм осадков в холодный период года на большей части Российской Федерации не наблюдается, а в арктических регионах Сибири и Дальнего Востока суммы осадков заметно уменьшаются.

Делается вывод, что практически на всей территории Российской Федерации со временем поправки к измеренным осадкам уменьшаются. Так, на картах разностей поправок (откорректированные минус наблюдённые осадки) между периодами с 1985 по 2010 г. и с 1958 по 1984 г. число отрицательных разностей намного превышает число положительных разностей. Среди причин такого уменьшения поправок – потепление климата в переходные сезоны, скачок в наблюдённых осадках в 1966 г., вызванный введением поправок на смачивание, и ослабление зимних скоростей ветра в Арктике.