PRECIPITATION TRENDS OVER THE RUSSIAN PERMAFROST-FREE ZONE: REMOVING THE ARTIFACTS OF PRE-PROCESSING

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ABSTRACT

Rain gauge changes, changes in the number of observations per day, and inconsistent corrections to observed precipitation data during the 20th century at the meteorological network of the former Soviet Union make it difficult to address the issue of century time-scale precipitation changes. In this paper, we use daily and sub-daily synoptic data to account for the effects of these changes on the instrumental homogeneity of precipitation measurements over the Russian Permafrost-Free Zone (RPF, most populous western and central parts of the country). Re-adjustments that were developed during this assessment allow us (a) to develop a system of scale corrections that remove the inhomogeneity due to wetting/observation time changes over most of the former USSR during the past century and (b) to estimate precipitation trends over the RPF reconciling previously contradictory results. The trend that emerges is an increase of about 5% per century. This estimate can be further refined after a more comprehensive set of supplementary data (precipitation type and wind) and metadata (information about the exposure of meteorological sites) is employed.

Key words: precipitation trends, wetting adjustments, Russia

1. INTRODUCTION

Each meteorological service improves its observational practice and instrumentation over time. The objectives of these improvements are different as these services meet/address different challenges/requirements. Homogeneity considerations of long-term climatological time series in the past had low priority on the list of these challenges. Now, when issues of global change studies raise the priority of homogeneous time series (Easterling *et al*. 2000; Førland and Hanssen-Bauer, 2000), we often pay a heavy price for non-optimal or even wrong decisions made many years ago. In this note we address an issue of the instrumental homogeneity of precipitation time series over the former Soviet Union during the 20th century and analyze the consequences of one of these decisions made circa 35 years ago to modernize the observational practice and improve the quality of precipitation measurements.

2. THE DIRECT STIMULUS TO CONDUCT THIS RESEARCH

Currently two research groups have conducted concentrated efforts to generate sufficiently complete archives of century-long homogeneous precipitation time series over the former USSR (Groisman *et al*. 1991, hereafter GRO; Gruza *et al*. 1999, hereafter GRU). Each group acquired the data set of monthly precipitation from more than 600 stations. Many of the stations included in these archives are the same, because GRU had an opportunity to consider the data available from GRO as one of the sources for their archive, and one of the objectives of both compilations was the same. Both groups intended to develop the longest possible precipitation time series over the country. However, the data sources and correction procedures used to secure the instrumental homogeneity of precipitation time series used by the two groups were different.

As a result, when we recently and independently used these two archives to estimate precipitation changes during the past century over the permafrost-free zone of the Russian Federation (RPF, Figure 1), we found very well correlated precipitation variations over this data-rich region (with R^2 up to 0.87; Figure 2). But, very different conclusions were drawn from the trend analysis based on these time series (Table 1). Table 1 provides our estimates of linear trends for seasonal and annual precipitation over the RPF based on GRO and GRU data sets. It shows that there is no discrepancy in linear trend estimates for the post WWII period (1951-1995), but both of the estimates are statistically insignificant and describe only 2% of the joint variance of annual RPF precipitation. All linear trend estimates for the past hundred years are positive and statistically significant at the 0.01 level, when they are based on the GRO time series. All trend estimates based on the GRU time series are insignificant. If each value of the GRU annual precipitation time series before 1936 is reduced by 20 mm (this value is empirical and arbitrary), then the appropriate GRU and GRO trend estimates become close to each other (last row of Table 1).

To illustrate the systematic differences that led to the contradictions shown in Table 1, we constructed three groups of differences between the annual and seasonal (warm April-September and cold October-March seasons) time series of RPF precipitation based on these two archives. We calculated differences based on all data in each archive (Figure 3A) on the data of the 92 stations that were found in both archives (Figure3B), and finally on those data points that were present in both archives (Figure 3C). The number of stations was changing throughout the century (Table 2), but the results shown in Figure 3 remain consistent. To better understand the nature of these differences, the next two sections briefly describe the history of precipitation observations in the former USSR and the details of corrections applied to the measured precipitation data by the GRO and GRU archive composers.

3. HISTORY OF PRECIPITATION INSTRUMENTATION AND OBSERVATIONAL PRACTICE CHANGES IN THE FORMER SOVIET UNION

For several reasons, it is very difficult to work with Russian precipitation data without proper preparation and extensive additional information (metadata). A short history of the precipitation observations in the former Soviet Union can be found in (Groisman *et al*. 1991; Golubev and Simonenko, 1996; and Bogdanova and Mestcherskaya, 1998). In brief, the following changes affected the homogeneity of the USSR/Russian precipitation time series during the 20th century at the primary meteorological stations (about 4,000 of them):

1. 1936: change from one to two precipitation measurements per day.
2. Late 1940s to early 1950s: gradual introduction of new Tretiakov-shielded rain gauges replacing the old Nipher-shielded gauges.
3. 1966: switch from two to four measurements per day over most of the country (except 7th, 8th, and 9th time zone - roughly East Siberia) and introduction of wetting correction (correction for retaining precipitation that reached the gauge collector/funnel but never reached the measuring glass) of 0.2 mm to each non-zero precipitation measurement.
4. 1967: reduction of the wetting correction for frozen precipitation from 0.2 mm to 0.1 mm. All other instructions remained valid.
5. 1986: Switch back from four to two per day observation times for most of the former USSR except the 3d time zone (western Russia, The Ukraine, Byelorussia, and the Baltic States).

3.1. Instrument change

The most dramatic effect on the homogeneity of the USSR precipitation time series occurred due to the gauge change in the late 1940s - early 1950s. The new gauge (and its shield) has better aerodynamic properties than the old one. Since the new gauge introduction, frozen precipitation has been measured with more accuracy: more snowfall is caught by the gauge and less snow is blown out of it once caught due to decreased turbulence over its orifice (Tretiakov, 1952; Shver, 1965; Sevruk 1982, Golubev *et al*.1999). The increase (sometimes by many tens of percent) in measured precipitation became so prominent that specialists who analyzed precipitation time series over the former USSR were able to estimate the jump in the data and account for it in their analyses even without the a priori knowledge of the instrument change (Dai *et al*. 1997).

The Russian meteorological service foresaw the problem and organized a nationwide four-year-long intercomparison of the two gauges. Shver (1965) assessed the results of this intercomparison and developed a procedure for estimating mean climatological monthly adjustment factors (know as K1) as function of station exposure, precipitation type, and wind speed. For the seasons with liquid precipitation K1 = 1, for the cold season K1 > 1 (except very well wind-protected sites where K1 = 1 also). K1 factors were then calculated for each location (where it was possible) and published in the Reference Books on the USSR Climate (Hydrometeorological Service of the USSR, 1967-1970) together with the dates of the new gauge installations. Therefore, if the researcher wants the instrumentally homogeneous precipitation time series over the entire period of observation, he must multiply the value reported by the old gauge by K1. Regretfully, for the sites with strong winds in the cold season (Arctic, sites along the Pacific coast), the accuracy of the high winter values of the K1 estimates (for K1 > 2) was low (the ratios of old and new gage measurements have a very high variance). Thus, it was considered inappropriate to publish and thus to use these factors. The homogeneity of cold season precipitation time series at these sites was, thus, irreversibly broken.

Another problem with the K1-adjustment in the cold season is that K1 is a steep function of the site exposure. Therefore, the published coefficients were valid for the period just before the introduction of the new gauge. If the site location had been changed before this date, and the site had its wind exposure substantially changed, then unspecified biases in the "instrumentally homogeneous" frozen precipitation time series were introduced. However, the original time series were inhomogeneous after such relocation to start with, even before this procedure, due to a significant effect that wind introduces to the measured amount of precipitation (so called wind-induced bias) (Kurtyka, 1953; Struzer *et al*. 1965; Bogdanova 1966; Sevruk 1982; Nespor 1996).

The bottom line of this section is that the researcher who uses the former Soviet Union precipitation time series should know the K1-coefficients (or that the K1-adjustment has already applied to the data), if he plans to work with the century-long cold season precipitation time series. Furthermore, having this information at hand, he will also need to collect all possible metadata related to site relocations that affect wind flow over the instrument: in the cold season even minor changes in the environment nearest to the gauge may crucially affect the amount of measured precipitation, introducing spurious trends in measured precipitation time series.

3.2. Different number of measurements per day

The increase of the number of precipitation measurements per day provides additional information about the diurnal cycle, but this also is a mixed blessing for the accuracy of the daily precipitation total estimates (Struzer, 1975). The shorter the interval between observations, the smaller the amount of precipitation measured. In climates with numerous precipitation events of low intensity (such as in northern Russia and Canada), these small amounts can become close to the random and/or systematic error of a single observation. For example, the rain gauges in Russia report precipitation with a 0.1-mm precision, but the wetting error of each measurement mentioned above is 0.2 mm for rainfall and 0.1 mm for snowfall. Moreover, the contribution of corrections for this error can be comparable to (or even exceed) the actual measured amount of precipitation. A diligent observer, following all present day instructions in St. Petersburg, Russia (as an example), while retrieving 0.1 mm each time during a day with drizzle from his gauge (total = 0.4 mm), must add to this value a 0.2 x 4 = 0.8 mm of wetting correction and report a daily total of 1.2 mm. This may be a more realistic precipitation estimate but illustrates that the relative weight of corrections can be a large portion of daily and monthly totals. A small miscalculation in this correction, and a bias that changes with time (and thus generates spurious trends) due to different number of measurements per day are guaranteed. Below we shall show that this indeed was the case.

3.3. Wetting correction.

Climatological values of wetting corrections (so called K3-coefficients) have been calculated for twice daily precipitation measurements at each station of the former USSR and published in the Reference Books on the USSR Climate (Hydrometeorological Service of the USSR, 1967-1970). Their implementation adds 5 to 15% in annual totals throughout the entire Russian Federation and up to 30% in the north of Russia in winter. The wetting corrections are introduced for volumetric measurements (i.e., when the precipitation collector is emptied into the measuring glass). They include the part of real precipitation that adheres to the collector wall and/or the gauge funnel stays there for a while and then evaporates. Thus, it is "lost" and should be accounted for in each single measurement. Numerous tests show that this is the case for rainfall on a warm day and for twice daily measurements (Struzer *et al*. 1965; Nechaev 1966; Struzer and Nechaev 1968).
But, when the number of measurements per day is increased, the interval between these measurements becomes shorter, and when there are several precipitation events, it is not so clear what happens with these “losses”. Moreover, during precipitation measurements in the cold season, the gauge should be taken into a warm room in order to melt the snow in it. Thus, inevitable condensation on the gauge (including inside the collectors' walls) makes the situation very uncertain.

Wetting corrections were developed for a particular observational practice of 12-hourly observations (Nechaev, 1966). Wetting and evaporation losses partially complement each other: when the number of observations increases, the wetting of the walls of the container increases, and thus the wetting losses may increase, but the evaporation from the gauge container decreases. Recent work by Bogdanova and Mestcherskaya (1998) shows that wetting losses have not increased (or even decreased) with a switch from the 2 to 4 per day observation schedule. But, corrections that diligent observers insert into the data increased by definition (they are proportional to the number of non-zero observations, which increased after this switch). Furthermore, Bogdanova and Mestcherskaya (1998) demonstrated that the published K3 coefficients are higher than they should be, due to the alteration during the practical implementation of the K3 evaluation scheme. The scheme recommended smaller variable K3 coefficients for the cold season months, but a laborious procedure was replaced by an easy one with significant simplifications and positive biases. The K3 coefficient corrections were initially suggested for accounting of the wetting losses in the long-term mean monthly values and their use for correction of the individual monthly precipitation totals introduces an additional random error with a zero mathematical expectation. Shver (1976) argued that this error is small.

The above indicates that the most serious concerns of climatologists involved in the development of these corrections and their usage are justified. The corrections that were introduced to bring the precipitation measurements toward the "ground truth" values have a serious flaw in the methodology of their implementation in the present network. Moreover, this flaw introduces an uncertainty in each precipitation time series over a huge country. The objective of this note is to constrain this uncertainty and to estimate its consequences to the assessment of precipitation trends over the former USSR.

3.4. Wind undercatch

Turbulence over the gauge orifice is the most difficult obstacle for the accurate estimation of the “true ground” precipitation using rain gauge measurements (Sevruk, 1982). Worldwide WMO projects (Sevruk and Hamon 1984; Goodison *et al*. 1998) and arduous multidecadal field studies (Golubev, 1969, Golubev *et al*. 1995; Golubev and Simonenko, 1996; Golubev and Bogdanova, 1996) were devoted to this problem. Sophisticated adjustment procedures have been developed for all Russian rain gauge types (Bogdanova, 1966; Golubev, 1973; Sevruk 1982; Yang *et al*. 1995; Golubev *et al*., 1999) to convert the measured amount of precipitation into a "realistic and true" value.

All analyses in this paper were made for measured precipitation that was unadjusted for wind undercatch. We currently do not possess the necessary information (wind speed, site exposure) to account for this bias in the century-long precipitation time series over the former USSR. Therefore, reduction of the measured precipitation to the "true" homogeneous time series is beyond the scope of this paper.

4. DIFFERENT APPROACHES TO HANDLE THE WETTING CORRECTION BY THE GRO AND GRU ARCHIVE COMPOSERS

GRO and GRU archive composers were aware of the history of instrumental and observational practice changes over the former USSR during the past 100 years and accounted for them in their data pre-processing. Both groups accounted for the instrument change (K1-adjustment) similarly. Both groups accounted for wetting losses in their precipitation data also, but the methodologies that they used were different.

Groisman *et al*. (1991) initially removed the wetting correction from their data set for the period from 1966 to 1984 and then increased the "original" data with constant monthly correction factors using K3 coefficients. Before 1936 they used factors equal to (1+K3/2), and starting with 1936 factors equal to (1+K3). This procedure was very arduous, and since 1985 the current observations with corrections inserted by observers were used. The original GRO archive spans the period from 1891 to 1993. Thereafter it is routinely updated by the GTS climate monthly reports available at the U.S. National Climatic Data Center at Asheville, North Carolina (NCDC). With readjustment and update resulting from this work, the refined GRO archive is available from the NCDC web site for the 1891-1999 period (TD-XXXX).

Gruza *et al*. (1999) compiled their archive from several sources ordered by a set of priorities. The first priority was given to the 243 long-term stations of the monthly precipitation archive prepared in the Dept. of Climatology of the World Data Center B for Meteorology at Obninsk, Russia, including 101 stations designated for International Exchange (Archive TEMPOS, WDC-B, 1989). This data set contained monthly precipitation data adjusted first for the gauge change (using K1 coefficients) and for wetting (using 1+K3 factors) for the periods of both one and twice per day precipitation measurements (i.e., up to 1965). The current observations with corrections inserted by observers since 1966 were used thereafter. This data set was appended with the data of 65 monthly precipitation time series also prepared in the Dept. of Climatology of the World Data Center B for Meteorology at Obninsk, Russia, using the same correction technique as for the TEMPOS archive. A second priority was assigned to a dataset of adjusted monthly precipitation prepared by regional meteorological offices (RMO; the USSR territory was divided among 38 regional offices). For the period from the beginning of observations to 1965, RMOs relied upon the procedure developed by the Main Geophysical Observatory specialists for twice daily observational practice. This procedure also uses K1 factors (if available; otherwise K1 is considered equal to 1) and additional information about the monthly number of days with liquid, frozen, and mixed precipitation. The RMO procedure estimates an additive monthly wetting correction for individual months according to formula:

Wetting correction (mm) = 0.3 x N1 + 0.15 x N2 +0.2 x N3, (1)

where N1, N2, and N3 are the actual number of days with liquid, frozen, and mixed precipitation. This procedure does not distinguish the once and twice daily observational schedule, and the current observations with corrections inserted by observers since 1966 were used thereafter for these stations. The third priority when compiling the GRU archive was assigned to the GRO data set. A few raw unadjusted precipitation time series were included in GRU inadvertently (Table 3).

Thus, these two archives contain slightly different data with slightly different adjustment procedures applied to these data. The major difference in wetting adjustment procedures used in these two archives was prior to 1936. In the GRO archive, the wetting corrections were decreased twofold to account for the one per day observations while in the GRU archive the wetting adjustments were performed prior to and after 1936 in a way similar to the way they were initially introduced for the two per day observations.

The analysis of Figure 3 clearly shows that an important conclusion concerning the precipitation changes over the major agricultural and industrial region of the Russian Federation (as well as over other regions of the former USSR) is tainted not by the difference in the data sources but by an obscure procedure of wetting correction that must be implemented properly in order to secure observational practice consistency during the past 100 years. Therefore, in the next section we describe our efforts to test and re-assess the procedures of wetting adjustment, using two additional archives with finer time resolution (3- and 6-hourly and daily) of precipitation measurements over the former USSR (Razuvaev *et al*. 1993, 1995).

5. DESIGN OF THE EXPERIMENTS AND THEIR RESULTS

The daily precipitation and temperature data set for the period of observations from 223 first order former USSR stations (Razuvaev *et al*. 1993, updated, Figure A1) spans the entire period of record up to December 1998. Using this archive and our metadata (K1 coefficients) we were able to construct the time series of daily precipitation for the period from the beginning of observations to 1997 distinguishing the number of days with precipitation for each month and partitioning the monthly precipitation values at each station into particular precipitation types (frozen, liquid or mixed) using daily temperature at the same stations.

The 3-hourly (since 1966) and 6-hourly (from 1936 to 1965) archive of synoptic information from the same 223 stations (Razuvaev *et al*. 1995 updated) includes 6 or 12-hourly precipitation totals and present and past weather codes. For the period 1936-1965 two precipitation observations per day were available in this archive. After 1966 the number of observations varies as described in Section 3. Using this archive, we were able to construct the time series of daily precipitation for the 1936-1990 period, distinguishing the number of days with precipitation of each type and the precipitation totals for each precipitation type. Moreover, for each month we were able to calculate the number of days with exactly one, two, or more non-zero precipitation observations of each type.

The data set of 223 stations is one-third the size of both the GRO and the GRU archives. Table 2 shows that over the RPF this data set has few long-term time series that cover the entire century. Therefore, we do not intend to substitute our trend estimates shown in Table 1 with those based on this data set. But, having necessary information about the number of days and observations with non-zero precipitation, we can better understand which adjustment procedures would be more appropriate, and estimate the biases for different parts of the regional precipitation time series that can be explained by the various pre-processing procedures. Finally, we suggest a new and better adjustment procedure that fits our current understanding of the gauge-wetting processes and removes the loopholes in previous techniques used to take into account wetting losses.

The use of original precipitation and weather code measurements without time averaging for the sub-daily data set provides us with new opportunities. First of all, in these data we can completely remove wetting corrections from all observations after 1966 that were inserted by observers. Thus, this ill-conceived correction will not affect the following efforts to generate homogeneous precipitation time series. We must take into account the change in the number of precipitation observations per day (i.e., account for changes in wetting/evaporation losses related to the changes in the observation frequency). The wetting losses are in fact the same as evaporation losses (but from the walls and funnel of the gauge), and if general evaporation is miniscule (e.g., in winter) these losses should also be small. Therefore, we speculate (and the recent analysis by Bogdanova and Mestcherskaya (1998) support our way of thinking) that these two corrections should not be additive for 6-hourly observations. For a day with four non-zero rainfall measurements it would be enough to use two instead of four wetting adjustments of 0.2 mm. Similarly, for a day with several non-zero snowfall measurements it would be enough to use one adjustment of 0.1 mm. We name this new wetting adjustment procedure our “best bet”. For the period before 1936 our “best bet” wetting correction procedure uses actual wetting corrections (0.2 mm, 0.1 mm, and 0.2 mm) for liquid, frozen, and mixed non-zero precipitation instead of the 0.3 mm, 0.15 mm, and 0.2 mm corrections used in the RMO-procedure. We believe this procedure would be the best possible adjustment procedure to follow for a one-per day observation schedule used before 1936. It exactly imitates the present instructions to observers and results of field and laboratory studies of wetting losses from Russian rain gauges.

Both data sets, Razuvaev et al. (1993, 1995) contain the raw daily/sub-daily observational data , which were not initially adjusted, except for the wetting adjustment introduced at the time of observation since 1966. This allows the use of these two archives to assess the differences in GRO and GRU processing and to generate three more wetting adjustment procedures:

- The present observers' practice of wetting adjustments, i.e., using for correction of each daily precipitation value the formula

  $$\text{Wetting correction (mm)} = 0.2 \times M1 + 0.1 \times M2 + 0.2 \times M3, \qquad (2)$$

  where M1, M2, and M3 are the actual number of observations per day with non-zero liquid, frozen, and mixed precipitation.
- The “improved” present observers' practice of wetting adjustments, using for correction of each daily precipitation value the formula

  $$\text{Wetting correction (mm)} = 0.2 \times M1' + 0.1 \times M2' + 0.2 \times M3', \qquad (3)$$

  where $M' = \min(2,M)$, $M2' \le \max(0,\ 2 - M1' - M3')$, and $M1' + M2' + M3' \le 2$. The correction approach in (3) capitalizes on the Bogdanova and Mestcherskaya (1998) findings that an increase in the number of observations per day did not increase wetting losses and thus we should not correct for this increase.

- Furthermore, we believe that there should not be more than the once per day wetting correction for frozen precipitation. This leads to the formula

Wetting correction (mm) = 0.2 x M1' + 0.1 x M2" +0.2 x M3', (4).
where M2" = min(1,M), M2" ≤ max(0, 2 - M1' - M3'), and M1' + M2" + M3' ≤ 2.
We name this last adjustment formula our "best bet".

5.1. Experiment with the daily data set.

We applied the K1 (gauge change) correction and then GRO, GRU(K3), GRU(RMO), and “present observer” wetting correction techniques described above to this dataset for the period with two and one per day observations prior to 1966. The results of their intercomparison (Figure 4) show that we were able to reproduce the differences (and discrepancies) previously seen in Figure 3 for our two archives. We can repeat that for the RPF:

- The GRO correction is very close to our “best bet” procedure prior to 1936, but then it gives somewhat higher values of precipitation totals (by ~2% for the period of two-per-day observations and by 1.3% for the period of four-per day observations).
- In both seasons the use of the RMO-procedure and K3 corrections to the one-per day observation period (prior to 1936) delivers values substantially higher than the K3/2 correction used by GRO for this period of time. Respectively over the RPF, these corrections generate 2.4% and 4.2% average increases in annual precipitation totals compared to the “best bet” estimates.
- For the entire period of twice per day observations, 1936-1965, the results of the K3 correction are somewhat higher than the results of the RMO procedure.

To further address the differences in the GRO and GRU adjustment methodologies and to develop the best possible correction for the period after 1936, when multiple precipitation observations per day were used, we turn to the analysis of the sub-daily data set of precipitation and present weather code information (Razuvaev *et al*. 1995 updated).

5.2. Experiment with the sub-daily data set

An opportunity that can now be explored is an exact imitation of the current observers' practice and insertion of wetting corrections into the data prior to 1966. Furthermore, we can "improve" the observers' practice for the entire period of observations and insert these corrections as we "believe" appropriate (our “best bet”), using current knowledge of the gauge wetting processes, and compare it with all other procedures. This will give us the opportunity to estimate the effects of inadequate corrections in our major data sets and account for them.

Initially, we adjusted all precipitation time series for instrument changes with the help of K1 mean monthly coefficients. Then the following monthly precipitation time series were generated for the entire 1936-1990 period from the sub-daily data set:

- Time series without wetting adjustments;
- Time series K3-adjusted for the entire period since 1936 (i.e., multiplied by factor 1+K3 as was done by GRO up to 1984 and by GRU for 166 stations up to 1965);
- Time series of the RMO-adjusted precipitation for the entire period since 1936 (i.e., with the help of Eq. 1 as was done by GRU for 154 stations up to 1965);
- Time series of the present observers' practice of wetting adjustments using Eq. 2;

- Time series of the "improved" present observers' practice of wetting adjustments using Eq. 3; and
- Time series of our "best bet" adjustments using Eq. 4.

Then we compare all other corrections with our "best bet" correction variant in Figures 4 and 5.

Several issues were addressed during this set of experiments. Among them are:

What would happen if we completely eliminate wetting corrections from the data?

Figure 6 shows that during the period of 12-hourly precipitation observations, an annual deficiency of approximately 34 mm (or 7.4% of the measured total) will be generated over the RPF. For the period of 1 per day observations (before 1936, not shown) this deficiency decreases by ~6 mm. For the period from 1966 to 1985, when most of the RPF has four per day observations, this deficiency increases by ~ 5 mm. This last increase (even when we use Eq.4) occurred, because with a shorter period between observations more chances arose to record a second non-zero precipitation datum from one rain event than during the 12-hourly observation schedule.

It should be noted that in a group of prominent publications (e.g., Mestcherskaya and Boldyreva, 1988; Mestcherskaya and Blazhevich, 1990) this path was followed. All wetting corrections were eliminated from the time series used in these catalogs. Our analysis shows that the potential negative bias generated by this approach during the 1966-1985 period is practically constant and affects but little the homogeneity of precipitation time series in the major agricultural regions of the former USSR.

What would happen, if we apply wetting corrections to the data?

This is not an academic question. All precipitation data in all data streams that leave and/or are published in the former Soviet Union since 1966 include wetting corrections, and, if the researcher plans a study of the recent precipitation changes over this territory, he must account somehow for their pre-processing. Below we present our estimates of the absolute performance of the two types of wetting adjustment procedures applied to the GRO and GRU data during the period since 1936 based on comparison with our "best bet" procedure.

Absolute performance of RMO and K3-based adjustments during the period of twice per day observations (1936-1965). For the April-September period of twice per day observations from 1936 to 1965, both RMO and K3-based wetting adjustment procedures generate precipitation time series area-averaged over the RPF zone within a 1% proximity, with the K3-based adjustments being higher than the RMO adjustments. In a test of their absolute performance, Figure 5 shows that these procedures during the 1936-1965 period slightly overestimate actual wetting corrections by approximately +1.7% (K3-based adjustments) and +0.6% (RMO adjustments). For the October-March period, Figure 5 shows that the RMO adjustments give a 1.8% biased area-averaged RPF cold season precipitation time series, while the K3-based adjustments noticeably overcorrected this time series by approximately 5 mm or by +2.9 %. Summarizing the above, we conclude that during the 1936-1965 period, the RMO adjustment overcorrected annual precipitation totals over the RPF by 5 mm (or by 1.0%), while the K3-based adjustment overcorrected annual precipitation totals over the RPF by 10 mm (or by +2.0%).

Absolute performance of the K3-based adjustments during the period of four per day observations (used by GRO for the 1966-1984 period). This performance for the area-averaged RPF time series during the warm season is very close to the observer practice (Eq. 2) and differs from our "best bet" correction procedure by 1 - 3 mm (by less than 1%). For the cold season the

K3-based adjustment "overcorrects" the RPF precipitation time series by 2 to 5 mm (on average by 1.9%). In annual totals the K3-based correction overestimates wetting (on average by 1.2%).

Inhomogeneity due to inappropriate handling of wetting corrections after 1966

(a) period 1966-1985.

The corrections that are based on instructions to observers for the twice per day observational schedule are in fact the only corrections that were systematically studied in field conditions (Struzer *et al*., 1965; Nechaev, 1966; Struzer and Nechaev, 1968). However, they became obsolete at the very time they were recommended for implementation because the network switched to four per day precipitation observations. The comparison of our "best bet" set of wetting adjustments with those implemented during 1966-1985 throughout the RPF (Figure 5) show that the overestimation of the "wetting-corrected" measured precipitation was 3 mm, or 1.0%, and 7 mm, or 3.6%, during the warm and cold seasons, respectively. This generates positive biases in annual total wetting-corrected measured precipitation reported during this period of 10 mm (15 mm in 1966) or, on average, 2 %.

(b) period after 1985.

Approximately 30% of the RPF is located in the third time zone where the four-per-day precipitation measurements have been continued up to the present. Thus, the overestimation of the wetting corrections over the RPF has been preserved up to the present with the westernmost part of the RPF contributing most of the bias of 0.6% of the annual total (but 1.7% in the cold season).

The differences between the "improved" observer practice and our "best bet" procedure are confined only to the handling of frozen precipitation after 1936. They are not shown because we found them to be negligible even for the cold season (~1 mm with standard deviation of 0.2 mm for the RPF-averaged October-March precipitation totals). These differences are systematic (the "best bet" procedure delivers precipitation estimates that after 1936 are less than those based on the "improved" observer practice) and, although we believe that our "best bet" corrections are better, we have no field experiment data to support this belief. Therefore, both these adjustment procedures are justified and generate an uncertainty of 0.3% in annual (0.6% in the cold season) precipitation estimates for the entire period of record.

6. SUGGESTED ABSOLUTE/RELATIVE RE-ADJUSTMENTS TO THE GRO AND GRU REGIONAL RPF PRECIPITATION TIME SERIES AND THEIR EFFECTS ON TREND ESTIMATES

Table 4 and Figure 7 summarize our estimates of biases of seasonal/annual precipitation time series area-averaged over the RPF based on experiments described in Section 4. For other regions of the former Soviet Union these estimates are presented in Appendix 1. For the period prior to 1936 with a one per day observation schedule, these estimates rely upon the wetting corrections to each non-zero precipitation value inserted exactly as the observers had been instructed since 1967. For the following years, the estimates of biases of each wetting correction procedure are based on our "best bet" corrections, in which we reduce the recommended wetting corrections for frozen precipitation to a maximum of 0.1 mm per day with non-zero precipitation and discard all corrections in excess of 0.4 mm per day for liquid and mixed precipitation. Figure 7 clearly shows that our re-adjustments for wetting reduce positive precipitation trends in the GRO data and enhance them in most of the GRU data (except those of the GRU that originated from the GRO archive). Thus, after these re-adjustments have been applied to the GRO and

GRU data sets, the trend estimates based on these two archives converge. After re-adjustment using the Table 4 values, the RPF annual precipitation time series based on the GRO data set shows a 5.5%/100yrs increase during the 1891-1998 period that is statistically significant at the 0.01 level. Wetting corrections applied originally to the GRU data set were different for different time series inside the RPF zone (up to three correction sets at the same time; cf. Tables 3 and 4). If we select a weighted composite of the scale adjustments from Table 4 with weights proportional to the station distribution in Table 3, the adjusted GRU annual precipitation time series area-averaged over the RPF will have a 4.3%/100 years trend estimate during the 1891-1998 period. If we assume that "all" GRU wetting corrections were in fact the RMO corrections and then adjust the RPF annual precipitation time series from the GRU archive, using the appropriate values from Table 4, the trend estimate would be 3.3%/100 years. However, if we assume that "all" GRU wetting corrections were in fact the K3-corrections, then this trend estimate would be 5.6 %/100 years.

Appendix 1 describes another approach to the wetting re-adjustment based on the same set of experiments. In this approach we introduce scale re-adjustments for wetting for each period with constant observational practice to each station of the six regions of the former USSR. After we re-adjusted each monthly precipitation time series in GRO and GRU, the area-averaged annual RPF precipitation time series based on these two archives produce 5.3%/100yrs and 4.7%/100yrs linear trend estimates respectively for the period of 1891-1998 (Figure 8). The standard deviation of each of these two linear trend estimates is 1.8 (in the same units). Thus, a simple re-adjustment of wetting corrections previously inserted into each precipitation time series of the GRO and GRU archives removes the contradiction in trend estimates based on these two data sets.

7. DISCUSSION

A brief look through Figures 2 and 3 reveals a noticeable scatter in the differences between seasonal and annual RPF precipitation time series based on the GRO and GRU archives. Several factors contributed to this scatter. Among them are

- different principles of selection of the stations included in the archives;
- undocumented deviations from accepted data adjustment principles;
- different quality assurance procedures used by the archive compilers; and
- different sources of the data (some data sources were available to GRO and not available to GRU and vise versa).

But, all these discrepancies had a random character and did not distort the variability and trends of the area-averaged seasonal/annual precipitation time series. This averaging effectively reduces the random noise but is helpless against systematic time-dependent biases in the data introduced by different wetting adjustment procedures. Therefore, the major achievement of our assessment of the wetting bias was a reconciliation of our conclusions about the century-long trends over the former Soviet Union derived from the GRO and GRU archives. An accounting for systematic differences in the data pre-processing was a key to this reconciliation. Nevertheless, the estimates presented in this paper while being the most probable and based on all the data available to the authors in digital form, can be significantly improved, if most of the entire former Soviet Union precipitation network (up to 11 thousand stations in the early 1970s) and/or the supplementary information about wind speed, precipitation type, and the history of the station exposures (to account for the wind undercatch) become available for the analyses.

This study illustrates the challenges that proper data preprocessing represents for climate change studies and is part of a long list of similar difficulties, such as:

- the uncertainty with the bucket correction of sea surface temperature (Folland and Parker 1995);
- troubles with implementation of the WMO recommendation in 1949 to switch the total cloud cover measurements from tenths to octas (some large countries, including Russia, Canada, China, and the United States neglected this recommendation);
- introduction of new temperature sensors in the United States network (Quayle *et al*. 1991); and
- numerous changes in remote sensing instrumentation.

The major lesson from all these troubles is ***that each innovation had its price***. For most of the data users in the former USSR, who have an access mostly to the monthly aggregated precipitation data, this price was a contradiction of signs of precipitation tendencies (cf., Table 1). A final uncertainty of about 1%/100yrs in century-long annual precipitation trends over the Russian permafrost-free zone can be considered a minor price *after* it has been revealed. But, this uncertainty will be inserted into all analyses of contemporary climatic changes over Northern Eurasia that follow for many years to come.

More and more often, scientists make their conclusions based on a data source they trust without checking/questioning the manuals of observations and/or pre-processing routines. Only when two or more groups run into a contradiction, as happened in our case, arduous and painful fact-finding starts. It would be much better to centralize the efforts and provide researchers with well-documented baseline archives with pristine pre-processing and fine time and/or spatial resolution to test/verify their findings in climate change studies.

The study by Bogdanova and Mestcherskaya (1998) shows that the wetting corrections are not carved in stone. The field experiments related to wetting correction evaluation were performed in northwestern Russia in the 1960s and later in Finland and southern Ontario in the 1990s. But, then the results of these experiments were expanded countrywide (Struzer and Nechaev 1968; Mekis and Hogg 1999). Different climatic conditions over such large countries as Canada and Russia represent a danger that the corrections' "good" behavior can be non-representative of the other parts of these countries. Regretfully, we found that this type of danger can contribute to and even define the answers to questions concerning the contemporary changes of precipitation.

All major results of this paper were related to the Russian permafrost-free zone shown in Figure 1. This is the major agricultural, industrial, and densely populated region of the Russian Federation. Expansion of both types of experiments (daily and sub-daily) to other regions of the former Soviet Union is discussed in Appendix 1. This expansion delivers similar results except for East Siberia (7^{th} 8^{th} and 9^{th} time zones), where four-per-day precipitation observations had never been introduced.

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APPENDIX 1. Wetting adjustments and re-adjustments at individual stations

The Russian permafrost-free zone spans three regions with different observational practice (Figure A1). To date in the westernmost region, precipitation measurements are made four times per day, while over the other parts of the country this practice was discontinued in January 1986 (in Kirgizstan, the switch to the twice per day observational schedule occurred several months later). On the contrary, during the two decades from 1966 to1985 precipitation measurements were made twice per day only in East Siberia, while in the other regions of the former Soviet Union the four-per-day observations were conducted at the first order stations. The Reference Book on the USSR Climate (Hydrometeorological Service of the USSR, 1966-70) and Shver (1976) show that the field of K3 coefficients is very smooth: these coefficients change slowly over the geographic domain. Experiments in Section 5 have shown that these coefficients, when used for wetting adjustment (as well as the RMO procedure and the observational practice during the past 35 years), introduce subtle systematic changes that interfere with precipitation changes on the century time scale (trends). We discovered these changes using daily and sub-daily data from stations shown in Figure A1 for each observational practice (adjustment schedule) used throughout the century. For these stations for each year, t, during each period of constant observational practice we calculated our "best bet" wetting corrected seasonal/annual precipitation total, $P_{best,}$ and the same precipitation total, P_i, corrected with procedure X_i. Thus, each ratio, $R(t) = P_i / P_{best}$ represents a point estimate of the scale bias of the X_i-wetting adjustment procedure for the observational practice used in this region. By averaging R(t) by time and then spatially, we get stable estimates of regional scale bias of each wetting procedure. We calculate long-term mean station values of R for warm and cold seasons separately and then arithmetically averaged these values over the regions shown in Figure A1, the two most western of which were additionally divided into two parts (north and south of 55°N latitude). The results are shown in Tables A1 and A2 for each period and region of constant observation practice and pre-processing used in GRO and GRU. These tables present the scale readjustment factors, F_i, (in percent) that should be used to convert the precipitation value, P_i, adjusted by the X_i procedure into the "best bet" value P_{best} ; $P_{best} = (1+F_i) * P_i$. These re-adjusted values will secure the homogeneity of precipitation time series for the past century (at least in relation to the rain gauge wetting losses).

It is possible that the user will get "raw" USSR precipitation data as they are available from the observational network. These "raw" data already have the wetting correction inserted since 1966 and therefore are intrinsically inhomogeneous. In the absence of individual K3-coefficients, Table A3 provides a possible "first cut" solution that can be used to substantially improve the homogeneity of these time series. It should be noted, however, that in the cold season (i.e., in the season when frozen precipitation is possible) the "raw" precipitation data can be used in any time series analyses only since the introduction of the new gauge in the early 1950s.

Table 1. Linear precipitation trend estimates over the RPF using two archives.

Season	Period	GRO data, trend %/100yrs	R^2	GRU data, trend %/100yrs	R^2	Subset
Annual		8.4**	0.16	1.9	0.01	
Oct.-Mar.	1891-1998	8.7**	0.07	0.5	0.00	All
Apr.-Sept.		8.2**	0.10	2.0	0.01	
Annual	1891-1998	5.0**	0.07	0.9	0.00	92 stations
Annual	1901-1995	6.2**	0.08	-0.3	0.00	All
Annual	1951-1995	5.6	0.02	5.6	0.02	All
Annual	1891-1998	N/A		7.0**	0.09	All, but adjusted by –20mm for the period before 1936

****** indicate trend estimates statistically significant at the 0.01 level.

Table 2. Number of stations with January/July precipitation data available for averaging over RPF from the GRO and GRU archives and from the daily data of 223 stations available in Ruzuvaev *et al* (1993).

Data set \ Year	1891	1917	1936	1951	Maximum available
GRO archive, all stations	73/81	128/122	157/157	163/167	169
GRU archive, all stations	52/53	78/78	113/115	123/124	127
GRO archive, 92 common stations	40/44	62/61	70/72	71/74	76
GRU archive, 92 common stations	43/44	60/60	70/72	75/75	76
Common data points in both archives	33/39	55/57	65/70	69/73	75
Razuvaev *et al*. (1993)	12/14	20/23	26/44	52/54	58

Table 3. Number of stations of the GRU archive with different types of wetting correction.

Type of correction	The entire data set	Stations in the RPF
(1+K3) up to 1965 and observations thereafter	166	49
RMO up to 1965 and observations thereafter	154	73
GRO up to 1984 and observations thereafter	27	7
GRO up to 1965 and observations thereafter	8	0
Including incompletely corrected data (no K1)	>30	3
TOTAL	455	129

Table 4. Suggested adjustments for seasonal/annual precipitation time series area-averaged over the Russian permafrost-free zone shown in Figure 1. Re-adjustments are shown in percent of the presently available precipitation total (measured, adjusted to instrument change and wetting correction).

Period	GRO time series			GRU time series (K3)			GRU time series (RMO)		
	Annual	Apr – Sep	Oct - Mar	Annual	Apr - Sep	Oct - Mar	Annual	Apr – Sep	Oct - Mar
Before 1936	0.5	0.8	0.0	-4.2	-3.1	-5.8	-2.4	-2.1	-2.9
1936-1965	-2.0	-1.7	-2.9	-2.0	-1.7	-2.9	-1.1	-0.6	-1.8
1966	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1967-1984	-1.2	-0.9	-1.9	-2.0	-1.0	-3.6	-2.0	-1.0	-3.6
1985	-2.0	-1.0	-3.6	-2.0	-1.0	-3.6	-2.0	-1.0	-3.6
Since 1986	-0.6	-0.2	-1.7	-0.6	-0.2	-1.7	-0.6	-0.2	-1.7

Table A1. Same as Table 4 but for individual seasonal precipitation time series from the GRO archive in the different time zones shown in Figure A1.

Period	Time zone 3				Time zones 4-6				Time zones 7-9		Time zones 10-13	
	>55°N		<55°N		>55°N		<55°N					
	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar
Before 1936	0.6	0.8	1.2	0.8	0.5	-0.5	0.6	0.2	0.6	-0.6	0.4	0.3
1936-1965	-1.5	-1.8	-0.8	-1.8	-2.0	-3.4	-2.2	-2.8	-2.1	-5.0	-2.0	-4.0
1967-1984	-0.5	-0.3	0.0	-0.8	-0.8	-2.1	-1.4	-2.0	-1.7	-5.0	-0.2	-2.0
1985	-1.3	-3.4	-0.9	-2.5	-1.5	-4.8	-0.9	-2.5	0.0	-2.2	-2.0	-4.9
Since 1986	-1.3	-3.4	-0.9	-2.5	0.0	-1.9	0.0	-0.7	0.0	-2.2	-0.1	-1.8

Table A2. Same as Table A1 but for individual seasonal precipitation time series from the GRU archive in the different time zones shown in Figure A1.

Period	Time zone 3				Time zones 4-6				Time zones 7-9		Time zones 10-13	
	>55°N		<55°N		>55°N		<55°N					
	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar
Stations adjusted using (1+K3) factors prior to 1966												
Before 1936	-3.8	-5.1	-1.7	-4.1	-3.8	-6.7	-3.7	-5.1	-3.2	-9.1	-3.5	-4.1
1936-1965	-1.5	-1.8	-0.8	-1.8	-2.0	-3.4	-2.2	-2.8	-2.1	-5.0	-2.0	-4.0
Stations adjusted using the RMO procedure prior to 1966												
Before 1936	-1.9	-1.6	-1.9	-1.3	-1.8	-1.9	-2.2	-1.5	-1.7	-3.0	-1.6	-1.8
1936-1965	-0.5	-0.5	-0.7	-0.5	-0.5	-1.4	-1.1	-1.2	-0.6	-3.2	-0.5	1.8
All stations with wetting adjustments inserted by observers since 1967												
1967-1985	-1.3	-3.4	-0.9	-2.5	-1.5	-4.8	-0.9	-2.5	0.0	-2.2	-2.0	-4.9
Since 1986	-1.3	-3.4	-0.9	-2.5	0.0	-1.9	0.0	-0.7	0.0	-2.2	-0.1	-1.8

Table A3. Suggested regional wetting adjustments/re-adjustments to individual seasonal "raw" precipitation time series for the former USSR. Under "raw" we understand the precipitation measurements reported according to the concurrent observational practice.

Period	Time zone 3				Time zones 4-6				Time zones 7-9		Time zones 10-13	
	>55°N		<55°N		>55°N		<55°N					
	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar	Apr -Sep	Oct - Mar
Before 1936	5.0	6.7	4.2	5.8	4.9	5.7	4.9	5.4	4.5	7.8	4.3	4.8
1936-1965	6.4	9.2	5.1	7.5	6.4	8.4	6.1	7.3	6.0	9.6	5.9	6.0
1967-1985	-1.3	-3.4	-0.9	-2.5	-1.5	-4.8	-0.9	-2.5	0.0	-2.2	-2.0	-4.9
Since 1986	-1.3	-3.4	-0.9	-2.5	0.0	-1.9	0.0	-0.7	0.0	-2.2	-0.1	-1.8

FIGURE CAPTIONS.

Figure 1. Russian permafrost-free zone, RPF, boundaries used throughout this study.

Figure 2. GRO (heavy lines) and GRU (solid thin lines) time series of seasonal/annual precipitation over the Russian permafrost-free zone. Thiessen polygon averaging (Thiessen 1911) strictly inside RPF was used for both data sets.

Figure 3. Difference between seasonal/annual precipitation totals over the Russian permafrost-free zone estimated using Gruza (GRU) and Groisman (GRO) archives. **A**. All archive data are used in the analysis. **B.** A subset of the common 92 stations included in both archives is used in the analysis. **C**. Same as B, but only the data points available in both archives simultaneously are used.

Figure 4. Differences between the annual/seasonal area-averaged RPF precipitation time series based on the same archive of daily precipitation (Razuvaev *et al*. 1993, updated) but with different wetting adjustment routines, and those generated using the "best bet" wetting adjustment routine. The "Observer" routine is the routine currently used at the network. The GRO routine was used by the creators of the GRO archive for the period up to 1984. Up to 1965, compilers of the GRU archive used the RMO routine for some of their stations and (1+K3) factors (that coincide with GRO routine for the period from 1936 to 1965) for others (Table 1).

Figure 5. Differences between the annual/seasonal area-averaged RPF precipitation time series based on the same archive of sub-daily precipitation (Razuvaev *et al*. 1995, updated) but with different wetting adjustment routines, and those generated using the "best bet" wetting adjustment routine. "Observer" routine is the routine currently used at the network. The GRO routine was used by the creators of the GRO archive for the period up to 1984. Up to 1965, compilers of the GRU archive used the RMO routine for some of their stations and the GRO routine for other stations (Table 1).

Figure 6. Wetness correction deficiency in annual/seasonal area-averaged RPF precipitation time series based on the same archive of sub-daily precipitation (Razuvaev *et al*. 1995, updated). Absolute values of appropriate "best bet" wetness corrections are presented together with their values in percent of measured precipitation.

Figure 7. Estimates of biases (%) of mean annual RPF precipitation time series due to an inaccuracy of wetting corrections applied originally to the data of the GRO and GRU archives. The biases of the GRU-based time series were calculated under an assumption that "all" stations were corrected with the help of the K3-based adjustments, GRU(K3), or with the help of the RMO adjustments GRU(RMO).

Figure 8. Same as Figure 2, but after re-adjustment for wetting correction using Tables A1 & A2.

Figure A1. Regions with different observational practices and the station network of Razuvaev *et al* (1993, 1995) used in the estimation of re-adjustments.

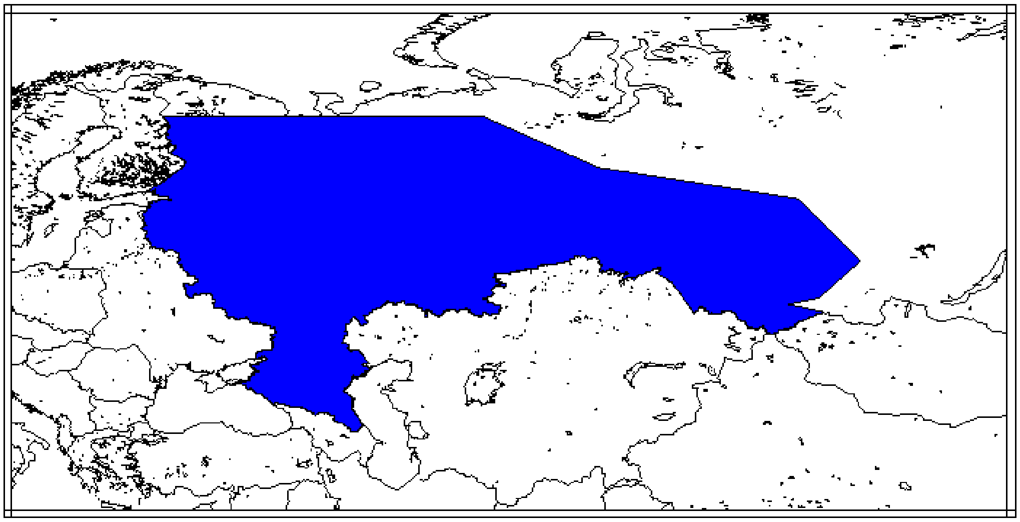


Figure 1. Russian permafrost-free zone, RPF, boundaries used throughout this study.

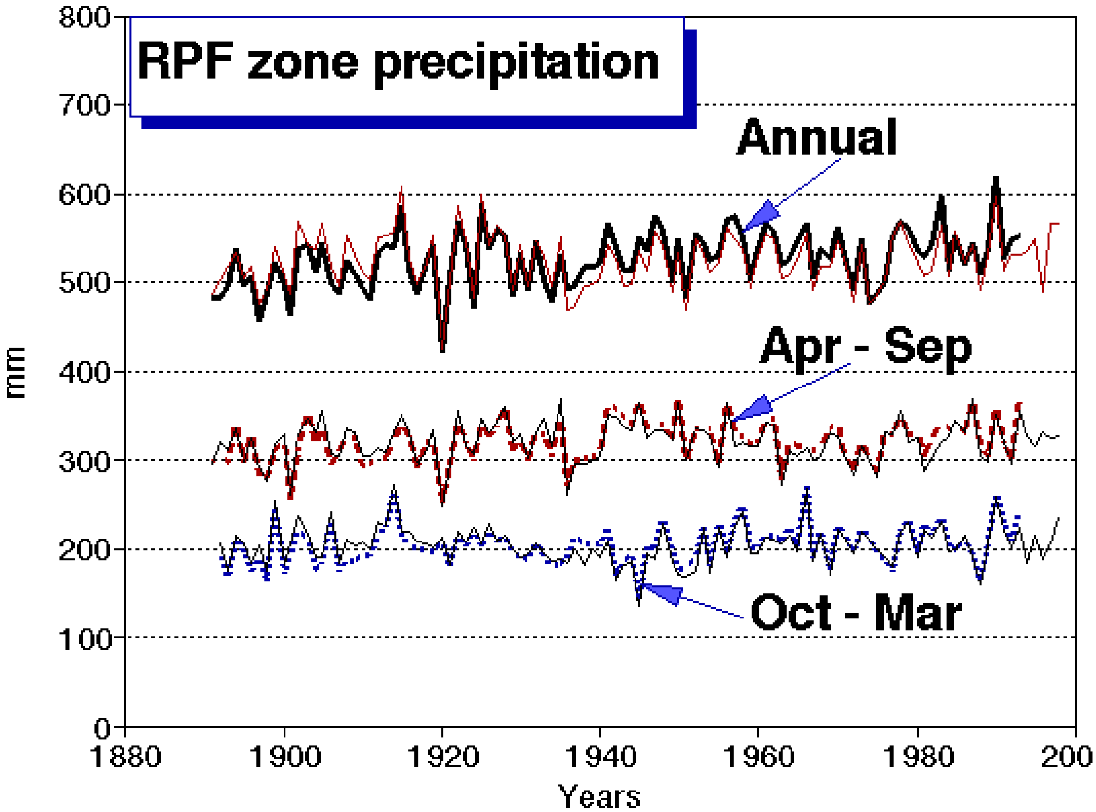
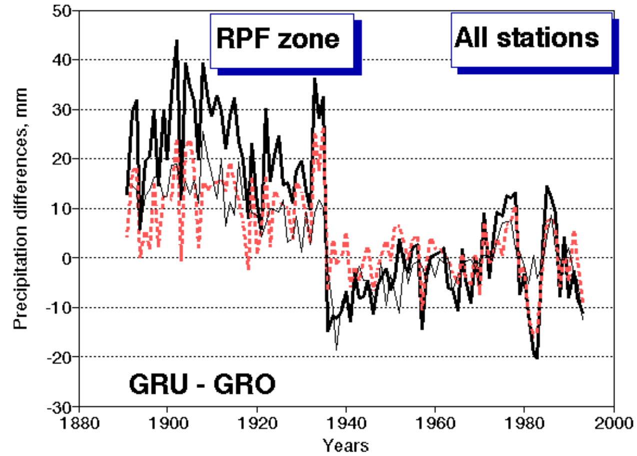
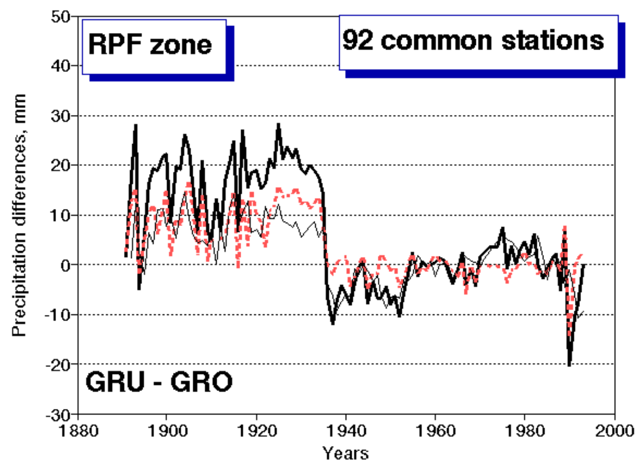


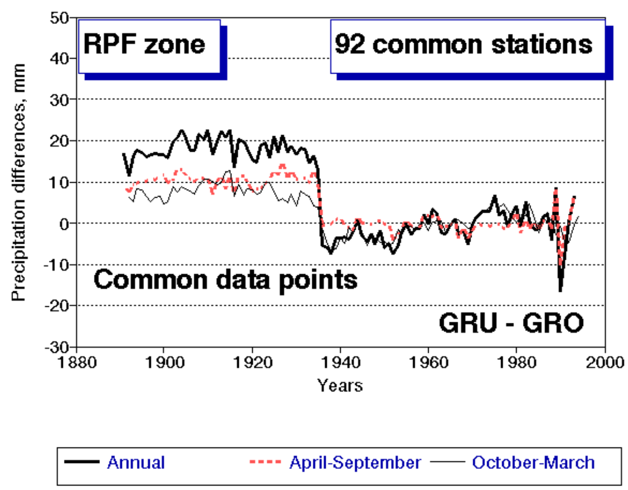
Figure 2. GRO (heavy lines) and GRU (solid thin lines) time series of seasonal/annual precipitation over the Russian permafrost-free zone. Thiessen polygon averaging (Thiessen 1911) strictly inside RPF was used for both data sets.



A.



B.



C.

Figure 3. Difference between seasonal/annual precipitation totals over the Russian permafrost-free zone estimated using Gruza (GRU) and Groisman (GRO) archives. A. All archive data are used in the analysis. B.A subset of the common 92 stations included in both archives is used in the analysis. C. Same as B, but only the data points available in both archives simultaneously are used.

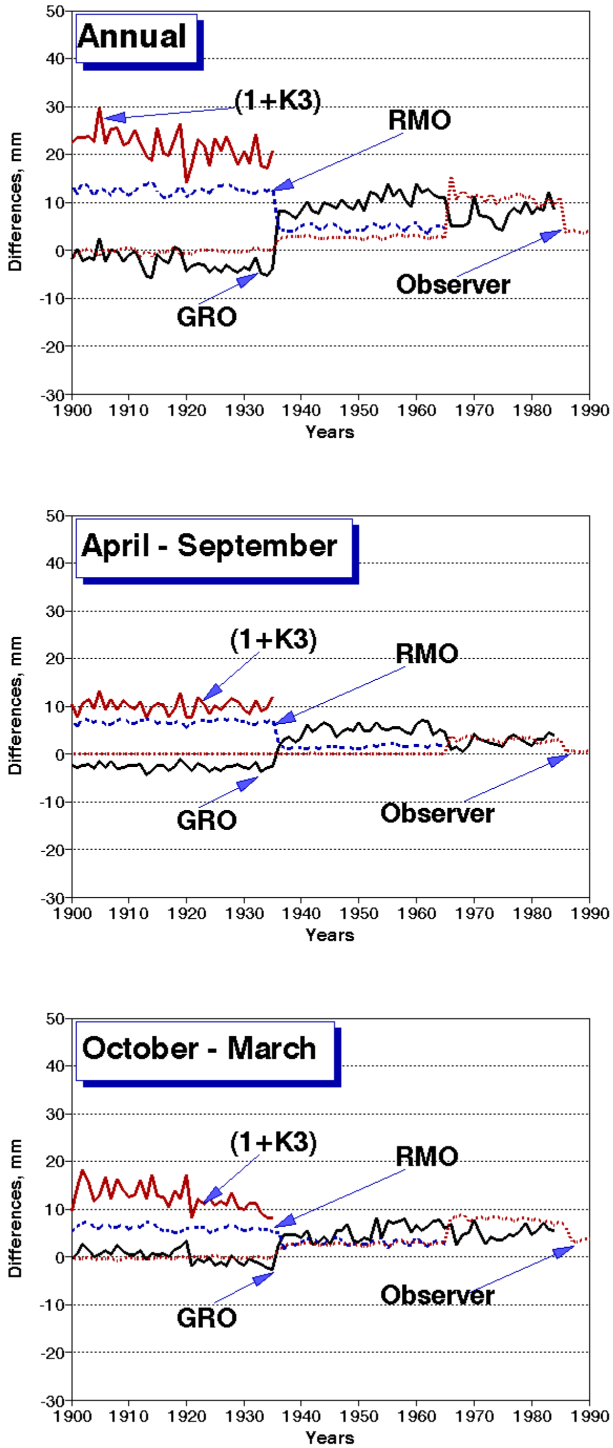


Figure 4. Differences between the annual/seasonal area-averaged RPF precipitation time series based on the same archive of daily precipitation (Razuvaev *et al*. 1993, updated) but with different wetting adjustment routines, and those generated using the "best bet" wetting adjustment routine. The "Observer" routine is the routine currently used at the network. The GRO routine was used by the creators of the GRO archive for the period up to 1984. Up to 1965, compilers of the GRU archive used the RMO routine for some of their stations and (1+K3) factors (that coincide with GRO routine for the period from 1936 to 1965) for others (Table 1).

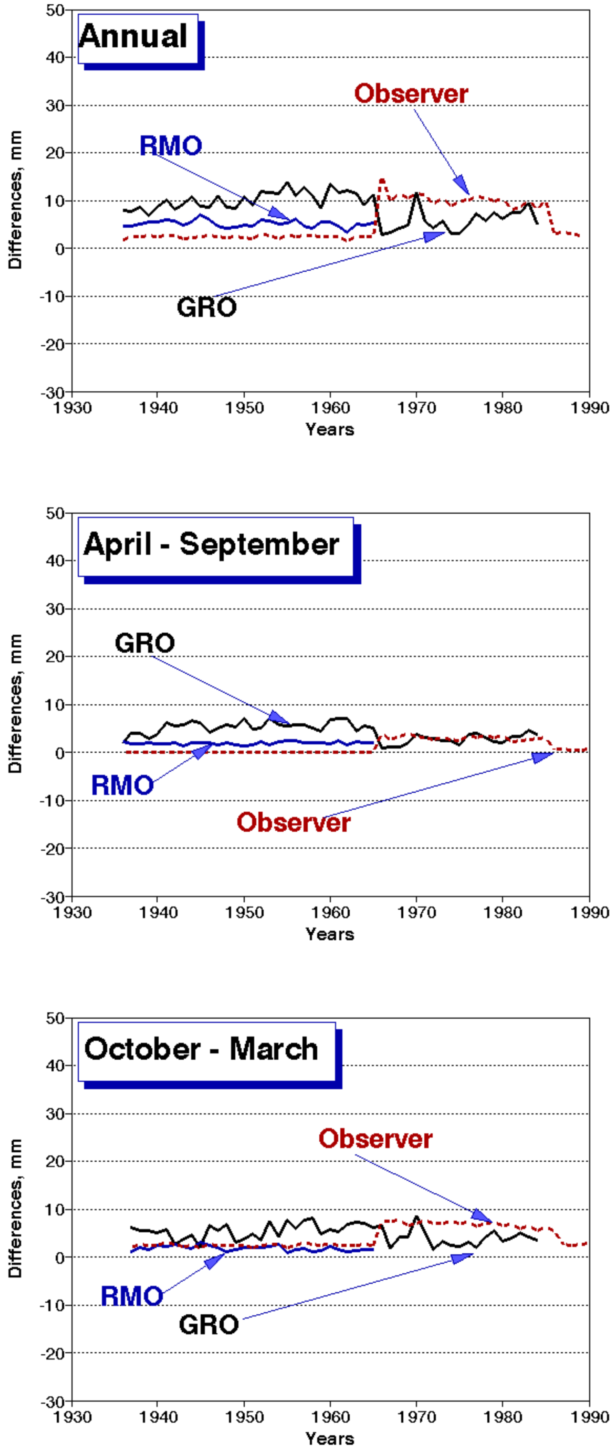


Figure 5. Differences between the annual/seasonal area-averaged RPF precipitation time series based on the same archive of sub-daily precipitation (Razuvaev *et al*. 1995, updated) but with different wetting adjustment routines, and those generated using the "best bet" wetting adjustment routine. "Observer" routine is the routine currently used at the network. The GRO routine was used by the creators of the GRO archive for the period up to 1984. Up to 1965, compilers of the GRU archive used the RMO routine for some of their stations and the GRO routine for other stations (Table 1).

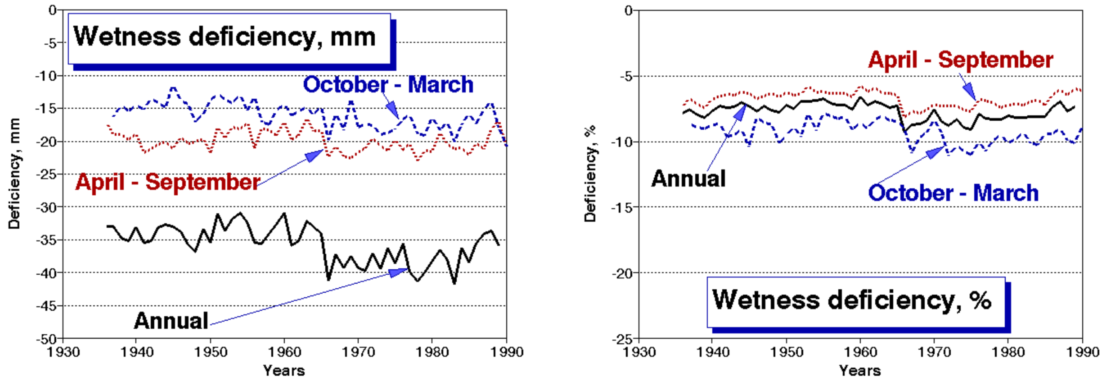


Figure 6. Wetness correction deficiency in annual/seasonal area-averaged RPF precipitation time series based on the same archive of sub-daily precipitation (Razuvaev *et al*. 1995, updated). Absolute values of appropriate "best bet" wetness corrections are presented together with their values in percent of measured precipitation.

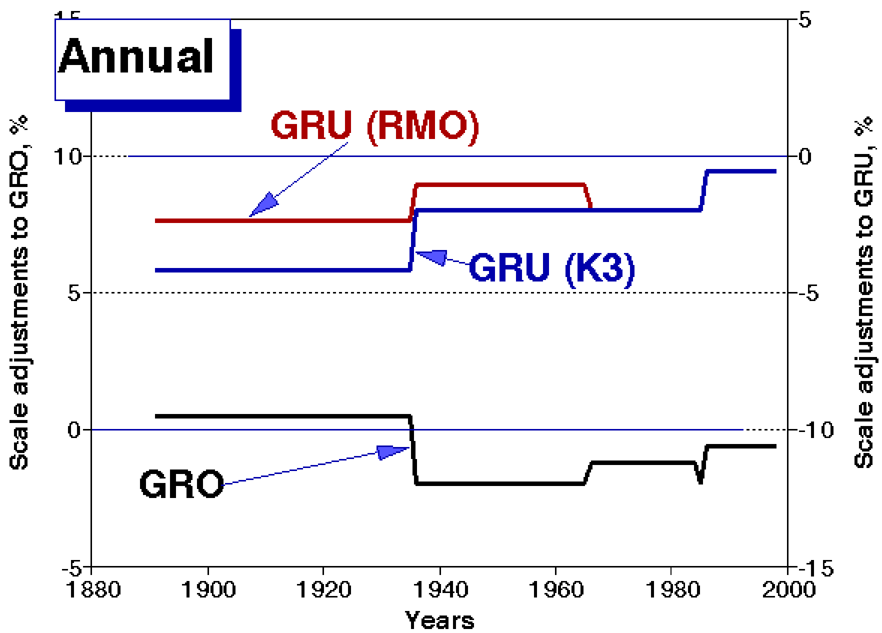


Figure 7. Estimates of biases (%) of mean annual RPF precipitation time series due to an inaccuracy of wetting corrections applied originally to the data of the GRO and GRU archives. The biases of the GRU-based time series were calculated under an assumption that "all" stations were corrected with the help of the K3-based adjustments, GRU(K3), or with the help of the RMO adjustments GRU(RMO).

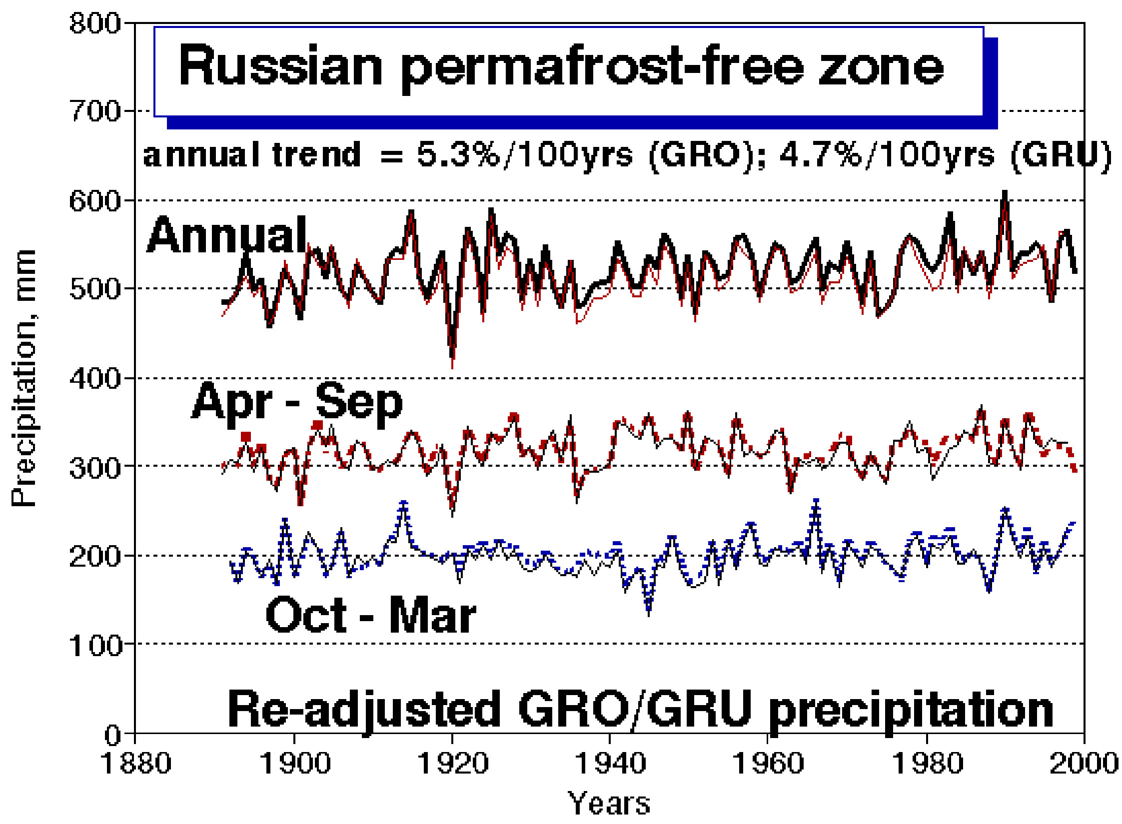


Figure 8. Same as Figure 2, but after re-adjustment for wetting correction using Tables A1 & A2.

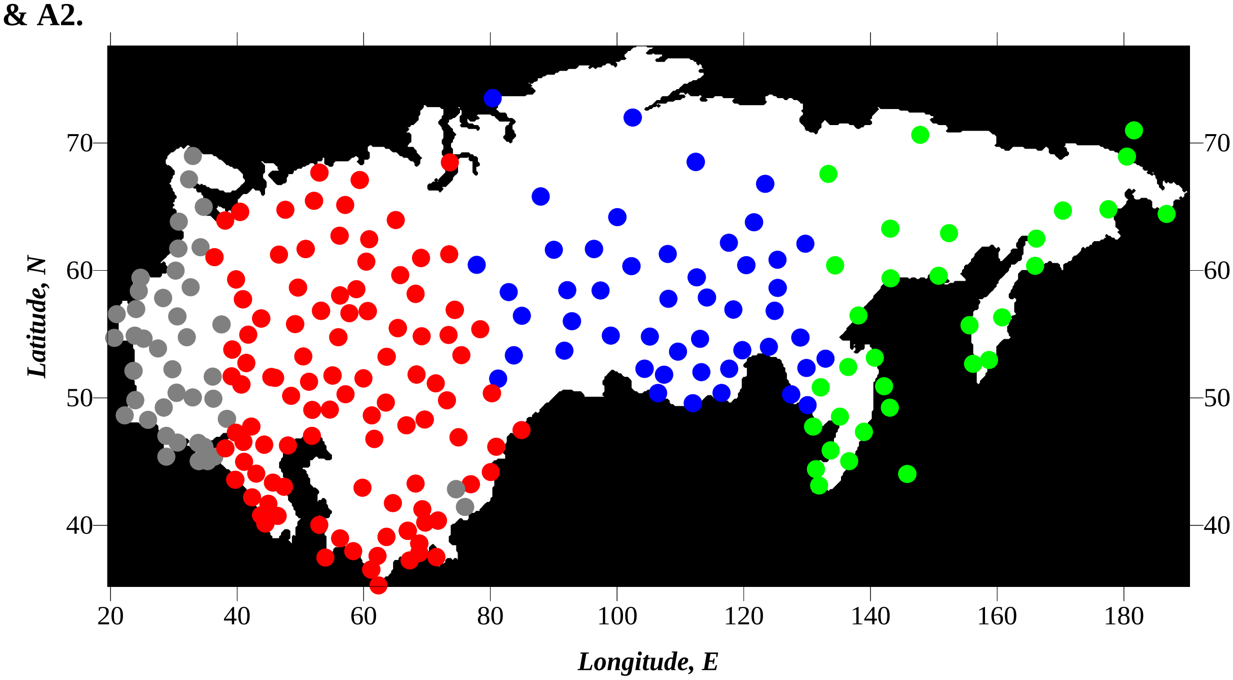


Figure A1. Regions with different observational practices and the station network of Razuvaev *et al* (1993, 1995) used in the estimation of re-adjustments.