On long period trend estimates of upper-air extreme and sub-extreme temperatures by use of quantile regression

A M Sterin and A S Lavrov

Russian Research Institute for Hydrometeorological Information – World Data Center (RIHMI-WDC) 249035 6 Korolyov str., Obninsk, Kaluga region

Abstract. The traditional studies of climate change are based on estimation of trends in average values of climate variables (such as monthly, seasonal, or annual average values of temperature, air pressure, precipitation, wind speed, etc.). However, these estimates do not provide detailed information on changes in the distributions and are not sufficient to answer questions about changes in extreme and sub-extreme values, as well as questions on left and right “tails” of the distributions and changes in the measures of variability. A mechanism called quantile regression (QR) is an instrument for performing such a study. Unlike the traditional regression methods that are based on the Ordinary Least Squares (OLS) methodology, QR can provide detailed information about the structure of climate trends for a whole range of values, i.e. including extremal and sub-extremal values. While the known climatological studies of QR trends in extremes and sub-extremes are related to surface meteorological variables, such as surface temperature, it is essential to make similar QR-based studies of trends for the upper-air (UA) temperature. This paper contains results of such an analysis for the UA temperature based on a collection of radiosonde data for more than 30 years of observation. We discuss typical patterns of a detailed structure of climate trends for the upper-air temperature in the troposphere and in the lower stratosphere for certain geographic sectors of the Northern Hemisphere. The existing difficulties to obtain realistic results in such a study are shown to be related to various kinds of gaps in the radiosonde data. Therefore, some data quality requirements are vital for such upper-air studies.

1. Introduction
The traditional approach for studying long-term climate changes is to assess long-term trends in the averaged values of meteorological variables (such as monthly or seasonal mean values of air temperature, pressure, wind speed, etc.) using the ordinary least squares method (OLS). The obtained OLS estimates have a significant drawback: they do not allow assessing the tendencies of changes in extreme and sub-extreme values of meteorological quantities, as well as tendencies of changes in the characteristics of variability of the meteorological quantities. These disadvantages can be solved by using the quantile regression method to estimate trends. Quantile regression is one of robust methods; the results of its estimation are insensitive to outliers.

The solution of the linear quantile regression problem for an arbitrary value of the quantile $\tau$ ($0 < \tau < 1$) is carried out by optimizing the following expression:

$$\hat{\beta} = \text{argmin} \left[ \sum_{i \in \{i: y_i \geq x'_i \beta \}} |y_i - x'_i \beta| + \sum_{i \in \{i: y_i < x'_i \beta \}} (1 - \tau) |y_i - x'_i \beta| \right].$$

(1)
In contrast to the solution of the linear regression problem by the ordinary least squares method, the solution of the linear quantile regression problem (1) cannot be found analytically. This problem is a convex linear programming problem and can be solved, for example, by the simplex method. The standard errors of solving this problem can be found by using, among others, the bootstrap method. The result of assessing the trends of meteorological quantities for different values of quantiles from 0 to 1 can be presented in the form of a process diagram. Figure 1 shows an example of a process diagram obtained from radiosonde temperature data at the Bodo station, Norway (WMO INDEX 01152) in the winter season (DJF) at a standard pressure level of 50 hPa for quantile values from 0.05 to 0.95.

![Process diagram example. 50 hPa temperature trend for DJF for Bodo station, Norway.](image)

Using the process diagram, one can judge about the features of climate trends at arbitrary values of the quantiles. For example, in Figure 1 the cooling of lowest temperature values is faster than the cooling of higher temperature values, which indicates an increase in the variability of meteorological parameters under study.

In the last years, a wider use of QR in meteorology and climatology may be noticed [1-3]. However, despite its advantages, the QR method in climatology and meteorology, especially in Russia, is used rarely. In Russia, the QR method was used by one of the authors to study trends in extreme and close to them values of surface temperature [4, 5]. This paper is devoted to a study of temperature trends in a free atmosphere using the QR method and radiosonde data as input. By now, there are no references to such application of the QR method in climatology.

2. Data

We used daily radiosonde data on the temperature at standard pressure levels (from 1000 to 30 hPa) from more than 900 upper-air stations from the global AEROSTAS data set. AEROSTAS contains data for Russian stations from 1979 to the present, and for foreign ones from 1984 to the present. For all data contained in AEROSTAS, a comprehensive quality control was applied. As a result of this control, a quality flag is assigned to each value of upper-air parameter, and so this flag was considered in the data analysis.

The number of available observations at a certain station is a significant problem due to data gaps. Therefore, for future analysis stations were selected that satisfy the following conditions:

1. The number of temperature values flagged as “CORRECT” during the winter (DJF) season for the Northern Hemisphere at the level of 50 hPa is not less than 40 (out of 90 max possible);
2. The minimal number of years that satisfy condition 1 is not less than 30.
In total, there were 363 stations over the globe satisfying both conditions 1 and 2. These stations were selected for further analysis of temperature trends in the free atmosphere using the QR method.

![Maps of station upper-air temperature observations as a fraction of maximal possible amount. Left - for 850 hPa, right – for 50 hPa.](image)

Figure 2. Maps of station upper-air temperature observations as a fraction of maximal possible amount. Left - for 850 hPa, right – for 50 hPa.

With such strict criteria of station selection, the selected stations, nevertheless, demonstrate an essential difference in the numbers of observations at different altitudes. Figure 2 shows maps of the average number of observations at the stations during the winter period at levels of 850 hPa and 50 hPa as a percentage of the seasonal maximum possible ones (90 observations). There is also a heterogeneity in the number of observations in different regions of the globe. North America, China, and Japan have, on average, more valid observations than Europe and Russia. This brings additional difficulties to analyze QR temperature trends, especially at high altitudes.

3. Calculation of linear trends
Estimation of the linear trends by the quantile regression method was carried out for values of the quantiles from 0.05 to 0.95 with an increment step of 0.01. The optimization problem (1) was solved by using the simplex method. The confidence interval was calculated by using a bootstrap with 200 subsampling repetitions. The significance level was 0.05.

Linear trend calculations were performed for each station of the four seasons: DJF, MAM, JJA, and SON.

As a result, for each station we obtained:
1. Process diagrams for all standard pressure levels;
2. Vertical-quantile sections of temperature trend values (X-axis – quantile $\tau$ values between 0.0 and 1.0, Y-axis – pressure or geopotential height values).

4. Vertical-quantile sections of temperature trends
The obtained vertical-quantile sections at individual stations show a complex structure of the linear trend values. As a sample, Figure 3 shows the vertical-quantile distributions of temperature trends in winter (DJF) for stations 01028 (Bjornoya) and 02185 (Lulea Kallax), both located in northern Europe.

In the troposphere, positive temperature trends prevail over the entire range of quantiles, while for the lower quantile $\tau$ values the trend values exceed those for $\tau$ closer to 1.0. That is, the coldest temperatures increase faster than the warmest ones. This indicates a decrease in the standard deviation of the time series values.

In the lower stratosphere, for both of these stations the temperature trends are negative for the whole range of $\tau$ values. One detail of the winter stratospheric cooling for the stations in the northern European sector presented in Figure 3 is that the decadal decrease in the temperature is more evident for higher values of $\tau$ than for lower values.
Figure 3. Vertical-Quantile sections of trends for stations 01028 (Bjornoya) – left and 02185 (Lulea Kallax) – right, for DJF season.

Figure 4 shows the vertical-quantile sections of the temperature trends in winter for two stations: 71917 (Eureka) and 71925 (Cambridge Bay) located in Northern Canada. For the troposphere, the patterns of wintertime warming are like those for stations in the northern European sector: the pattern of decadal tropospheric warming is not homogenous within the range of the quantile, so that the lowest temperatures are becoming warmer more rapidly than higher temperatures. This is in agreement with our previous estimates that were made for the northern part of the territory of Russia for winter surface temperature [4, 5].

In the lower stratosphere of the American sector, the pattern of QR trend change for most of the stations is a stronger cooling tendency for the lower values of the quantile \( \tau \) than the cooling tendency for values of the quantile \( \tau \) close to 1.0. Moreover, there were many stations in the sub-polar part of the American sector that demonstrated a winter stratospheric warming trend for values of the quantile \( \tau \) close to 1.0 rather than a cooling trend. At the same time, for lower values of \( \tau \) these stations demonstrated an obvious cooling trend (a more contrasting situation than the one demonstrated in Figure 4).

Figure 4. As for Figure 3, but for stations 71917 (Eureka) – left and 71925 (Cambridge Bay) - right.

Uneven distribution of the temperature trends depending on the quantile values is observed in other seasons as well. As a sample, Figure 5 shows the vertical-quantile distributions of temperature trends in summer (JJA) for stations 70316 (Cold Bay) and 71600 (Sable Island N.S.) located in the temperate latitudes of North America. Note that for the troposphere the pattern of summer warming, like that of winter warming, is not homogenous within the range of quantiles, and the lowest temperatures are becoming warmer more rapidly than higher temperatures.
5. Discussion
A detailed assessment of QR trends in radiosonde temperature observations for different geographic sectors of the Northern Hemisphere and for all four seasons was provided. In this paper, we provide only a limited number of samples of the vertical-quantile sections, though a large amount of calculations and graphical materials was assessed. One important result is confirmation of the tropospheric warming. The tropospheric warming in the Northern Hemisphere is not homogenous within the range of quantile. Therefore, the lowest temperatures (quantile $\tau$ close to 0.0) are becoming warmer more rapidly than the higher temperatures (quantile $\tau$ close to 1.0).

Another topic for discussion is the stratospheric cooling. In brief, estimates of temperature trends in the lower stratosphere in spring, summer, and autumn confirm the stratospheric cooling. We do not discuss all possible aspects of the results, but concentrate more on wintertime trends in the lower stratosphere of the northern temperate and the polar latitudes.

We believe that there could be two aspects in the above-obtained structure of stratosphere QR trends in the winter temperature in the polar regions.

One aspect is that a possible physical explanation for the positive values of QR trends at high values of $\tau$ could be changes in the frequency and amplitudes of sudden stratospheric warming (SSW) episodes. According to [6], the number of SSWs tends to increase. Moreover, a record number of SSWs for 2000-2009 followed an extremely low number of SSWs in 1990-1999. Numerous other publications confirm not only the fact of increasing frequencies of SSW events but an increase in their amplitudes and an increase in their span over calendar dates as well.

The other aspect in a possible explanation of the lower stratosphere winter QR for the polar region trends is radiosonde data quality and data amount. A detailed assessment shows that physically explainable and realistic results are obtained for stations with greater amount of the data. At the same time, the insufficient amount of lower stratosphere data and the differences between the data amount along the temperature vertical profile can lead to artefacts and to physically unexplainable results. Strong cold conditions in the stratosphere could lead to lower ceiling values of radiosonde flight altitudes. Therefore, the sample of temperature values poorly presents most cold events (they correspond to $\tau$ close to 0.0). At the same time, in this situation the sample contains unevenly more values of less cold conditions that correspond to relatively large values of $\tau$.

In situations when calculations of separate parts of vertical-quantile sections for QR trend estimation are presented by values in an essentially different way, the results of an analysis based on such graph may be questionable. Nevertheless, QR can be considered as a proper powerful instrument for the study of detailed patterns of climate trends in the free atmosphere based on observational radiosonde data.
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