Comprehensive analysis of snow cover in the south of Russia

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Abstract: Snow cover is one of the components of the natural environment that determines the weather and climate. In recent decades, there have been changes in all characteristics of the snow cover, which are associated with climate warming. This work is devoted to the analysis of changes in various characteristics of snow cover in different climatic zones of the Caucasus region for the period 1960-2018 and the construction of a regression model of seasonal variability of snow cover thickness (SCT) in the south of the European territory of Russia (ETR). Based on the data from the series of snow cover thickness, the number of days from the snow cover (SC), the dates of the beginning and end of the SC descent, the dates of the establishment / destruction of the stable SC in the cold seasons of 1961-2018 in the south of the ETR, an assessment of the change in these characteristics was carried out. As a result of the analysis, it was found that, against the background of global warming, the number of days with snow cover decreases, the dates of the beginning and descent of a stable SC are shifted towards a reduction in the duration of the SC occurrence, and at the same time, an increase in the SC height is observed. A regression model of seasonal variability of the thickness of the snow cover has been built. The analysis of the seasonal variability of the SCT showed that the thickness of the snow cover for the southern regions of Russia has a pronounced seasonal variation with a determination coefficient no worse than 55%. The fields of the parameters of the seasonal variation are quite smooth, and their variability is well physically conditioned.

1. Introduction
Changes in the regime of winter precipitation and snow cover can be considered a complex indicator of the climate of the cold season, reflecting changes in the temperature regime, precipitation regime, the frequency of thaws, etc., affecting the vital activity and productivity of natural ecosystems and agricultural crops.

Against the background of global warming observed in recent decades, changes in all characteristics of the snow cover are taking place. With a warming climate, it is expected that the area of snow cover will decrease in a significant part of the country. In addition, it should be emphasized the importance of knowing the patterns of distribution of snow cover for assessing the hydrological resources of the country [1-3].

This article presents the results of an analysis of changes in various characteristics of snow cover in different climatic zones of the Caucasus region over a long period (1960-2018) with the subsequent construction of a regression model of seasonal variability of snow cover thickness (SCT) in the south of the ETR.
2. Materials and research methods
To assess the change in the characteristics of the snow cover, we used the data from the series of snow cover thickness (SC), the number of days from the SC, the dates of the beginning and end of the SC descent, the dates of the establishment / destruction of a stable SC in the cold seasons of 1961-2018 in the south of the ETR. To obtain the results of changing the snow cover regime from 1960/1961 to 2017/2018 on the territory of the Caucasian region, the averaged series of snow cover characteristics were studied according to data from ten weather stations (w/station), which were represented by a full set of SP characteristics: Izobil’nyi, Maykop, Prokhladnaya (flat zone, <500 m above sea level (a.m.)), Vladikavkaz, Kamennomostsky, Kislovodsk, Nalchik, Stavropol, Cherkesk (foothill zone, 500-1000 m above sea level) and Teberda (mountainous, 1000-2000 m above sea level). To obtain the average annual series, the average ten-day heights were averaged over 7 months (October, November, December, January, February, March, April) of the cold seasons 1960/61 - 2017/18.

3. Research results and their discussion
For such a diversified region as the south of the ETR, the average snow cover characteristics are presented for the plane, foothill and mountain zones in table 1.

Table 1. Statistical characteristics of the snow cover regime in climatic zones for 1960/1961-2017/2018.

| Characteristics | SCT, cm | Number of days with the SC | Date |
|-----------------|---------|---------------------------|------|
| Average (srt.dvt), $\bar{x} \ (\sigma)$ | 4.6(2,3)c m | 49(18) days | (19 days) |
| Climate norm (1961-1990 rr.), N | 4.1 cm | 49 days | 22nd November |
| Trend, a/10 yrs | 0.3 cm /10 yrs | -0.6 days /10 yrs, | 22nd November |
| Determ.coef. $D$, % | 5.6% | 0.2% | 0.1% |

| Date | end of SC | establishment of sustainable SC | destruction of sustainable SC |
|------|-----------|--------------------------------|-------------------------------|
| 24th November | 16th March | 4th January | 17th February |
| 22nd November | 15th March | 9th January | 24th February |
| 0.4 days | 2.0 days | -3 days | -5.0 days |
| /10 yrs | /10 yrs, | /10 yrs, | /10 yrs, |
| 0.1% | 4% | 5% | 11.2%* |

| Characteristics | SCT, cm | Number of days with the SC | Date |
|-----------------|---------|---------------------------|------|
| Average (srt.dvt), $\bar{x} \ (\sigma)$ | 5.5(4.0) cm | 65(21) days | 15th November |
| Climate norm | 4.7 cm | 65 | 14th November |
| Trend, a/10 yrs | 0.52 cm /10 yrs | 0.5 days /10 yrs | 0.3 days /10 yrs |
| Determ.coef. $D$, % | 6.4% | 0.1% | 0.0% |

| Date | end of SC | establishment of sustainable SC | destruction of sustainable SC |
|------|-----------|--------------------------------|-------------------------------|
| 25th November | 31st December | 23rd February | (20 days) |
| 29th December | 28th December | 24th February | |
| 0.3 days | -0.3 days /10 yrs | -1.5 days /10 yrs | -1.8 days |
| /10 yrs | /10 yrs, | /10 yrs, | /10 yrs |
| 0.0% | 0.1% | 1.7% | 1.0% |

| Characteristics | SCT, cm | Number of days with the SC | Date |
|-----------------|---------|---------------------------|------|
| Average (srt.dvt), $\bar{x} \ (\sigma)$ | 7.3 (5.0) cm | 89 (27) days | 3rd November |
| Climate norm | 6.5 cm | 83 days | 6th November |

| Date | end of SC | establishment of sustainable SC | destruction of sustainable SC |
|------|-----------|--------------------------------|-------------------------------|
| 13rd April | 15th December | 28th February | (20 days) |
| 14th December | 12nd February | 26th February | |
| 16 days | 26 days | (29 days) | |
| 12nd | 26th February | |

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The primary data of observations of 20 w/stations in the south of the ETR in cold seasons (October-April) since 1960/1961 were used as a source of SCT series for 2017/2018 provided by the Federal State Budgetary Institution «North Caucasian Directorate of Hydrometeorological Service». As a result of the study, an algorithm was built to create a model of the seasonal course of SCT in different climatic zones of the south of the ETR.

Table 1 shows that the average value of the average decadal height of snow cover in the cold seasons 1960/61-2017/18 increases as the height above sea level increases in different climatic zones: 4.6 cm (σ=2.3 cm) on the plain; 5.5 cm (σ= 4.0 cm deviation) in the foothill zone and 7.3 cm (σ= 5.0 cm) in the mountain zone. The average long-term values of the snow cover height (1961-2018) in all climatic zones exceed the climatic norm (1961-1990), but remain within the statistical equality of the average and the norm. The average number of days with snow cover for the studied period increases with increasing altitude: 49(18) days in the plain, 65(21) days in the foothill zone, and 89(27) days in the mountain zone. The average for the studied period and the climatic norm for the lowland zone and the foothill zone did not change. In the mountain zone, there was a slight increase in the number of days with SC, but the T-test at the 5% level did not reveal a statistical difference between these values.

The average rate of change in the number of days with snow cover for the period 1961-2018 for the flat territory was ≪0.6 days /10 years». The trend is statistically insignificant (D=0.2%). Thus, for the period 1961-2018, there was a slight reduction in the duration of the period with snow cover at the lowland w/stations.

Of the six foothill w/stations, two (Cherkessk, Kislovodsk) located fairly close (R=64 km) showed a significant increase in the number of days with snow cover at a rate of 2 days/10 years and 3.8 days/10 years, respectively. In Nalchik, the rate of increase in the number of days with snow cover is small and amounted to 0.35 days/10 years. At the remaining w/stations, there was a tendency to decrease the number of days with snow cover at a low rate. The average rate of change in the number of days with snow cover for the period 1961-2018 for the foothill area was ≪0.5 days/10 years». The trend is statistically insignificant (D=0.1%). Of all the stations studied, the mountain w/station Teberda (1335 m a. s. l.) was distinguished, where the highest and statistically significant rate of increase in the number of days with snow cover a=5 days/10 years was obtained.

As a result of the statistical analysis of the dates of the beginning / end of snow cover in various climatic zones of the southern Russia, the following averaged dates were obtained: on the plain - November 24th (19 days) / March 16th (15 days); in the foothill zone - November 15th (20 days) / March 25th (15 days); in the mountainous area - November 3rd (20 days) / April 13rd (16 days). The displacements of the dates of the beginning / end of snow cover on the plain and foothill zone are statistically insignificant. In the mountainous zone, there is a statistically significant change in the date of the onset of the SC appearance to an earlier date at a rate of 4.0 days /10 years (D=7.9%).

Since we studied the south of the European territory of Russia, where a stable snow cover lasting from a month or more with small interruptions is an infrequent phenomenon, the series of dates for the establishment / destruction of a stable snow cover are discontinuous. On the plain, there was a statistically stable trend of the shift of the date of destruction of the stable SC towards the early dates by 5.0 days/10 years (D=11.2%).

Further, a study was carried out out of one of the most important characteristics of the SC – the seasonal variability of the mean ten-day snow cover thickness in different climatic zones of the south of the ETR. The primary data of observations of 20 w/stations in the south of the ETR in cold seasons (October-April) since 1960/1961 were used as a source of SCT series for 2017/2018 provided by the Federal State Budgetary Institution «North Caucasian Directorate of Hydrometeorological Service». As a result of the study, an algorithm was built to create a model of the seasonal course of SCT in different climatic zones of the south of the ETR.
To solve the problem of creating seasonal variability in the average ten-day snow depth over a long-term period, regression models were built, that is, a set of parameters representing the regression coefficients of the observation series for the harmonics of the period of snow availability in the region.

On the basis of a database containing series with the format: «record» – station, «field» – counting the thickness of the snow cover, the average counts for these decades were calculated. Based on real data (counts), a first approximation model is obtained.

The second approximation model was obtained using the known period $T_{21}$ ($T = 21$ decades) in the spectral Fourier expansion in three harmonics. With the help of the dialog box «Parameters for finding a solution» (EXCEL 10.0) and the function SEARCH FOR SOLUTION, the linear problem of optimization of finding the period of change in the thickness of the snow cover $T_i$ by the criterion of maximum closeness of the regression of the second approximation to the first (determination coefficient $R^2 = \text{max}$) was solved [4-6].

The parameters of the models were determined by the least squares method from the ratio:

$$h(t) = \sum_{k=1}^{3} [a_{ik} \cos \left(\frac{2\pi k}{T} t\right) + b_{ik} \sin \left(\frac{2\pi k}{T} t\right)] + a_0 + Rez_i(t), \quad (1)$$

where $k$ – is the number of decomposition harmonics; $t$ – is the duration of the cold season (October-April) in decades, starting from the 1st decade of October (21 decades in total); $h_i(t)$ – averaged over the entire observation period of SCT at the $i$-th station for the decade $t$; $T$ – is the duration (in decades) of the period of snow cover in the region, $T=21$ decades.

In the regression model (1), the values of the coefficients $a_{ik}$, $b_{ik}$, calculated by the least squares method, were tested according to the Student's test, and those whose reliability was less than 95% were assumed to be zero. The number of harmonics in our models is limited to three ($k=3$), which follows from certain considerations: Kotelnikov’s theorem [2] requires at least two samples per period, but it is valid only for an infinite value of the signal-to-noise ratio. Therefore, we test harmonics that have at least three counts per period, but no higher than the seventh. Evaluating the constructed models of seasonal variability, one should recognize them as sufficiently reliable and effective for solving a number of practical problems, in particular, such as, for example, forecasting yield. Using the LINEST function, statistics were calculated for the regression model of the seasonal variation of SCT ($T=21$ decades), including the coefficient of determination, Fisher's statistics, and Student's statistics to determine the statistical significance of the obtained coefficients. The result was a model of seasonal variability of the thickness of the snow cover (cm) in the cold season (October-April) in different climatic zones of the south of the ETR ($T=21$ decades, table 2).

### Table 2. Seasonal variability of SCT according to the model data ($T_i = 21$ decades).

| Decades | 05th | 15th | 25th | 5th | 15th | 25th | 5th | 15th | 25th | 5th | 15th | 25th |
|---------|------|------|------|-----|------|------|-----|------|------|-----|------|------|
|         | Oct. | Oct. | Oct. | Nov. | Nov. | Nov. | Dec. | Dec. | Dec. | Jan. |
| SCT, cm | 0.132 | 0.0 | 0.251 | 0.993 | 2.0130 | 3.048 | 3.929 | 4.681 | 5.448 |
|         | 5.293 | 6.293 | 7.049 | 7.357 | 6.881 | 5.561 | 3.716 | 1.905 | 0.627 | 0.026 | 0.142 |

The value of the determination coefficient $R^2 \geq 0.07$ (at the station of freedom $df = 56$) determines the statistical significance of the trend in the change in the thickness of the snow cover (Stavropol, $R^2 = 0.08$) from which it follows that only at Stavropol station there was a statistically significant trend in the change in altitude snow cover. The value of the significance of the Student's coefficient $\text{Sig}_S \leq 0.05$ (with a 95% confidence interval) determines the statistical significance of the change in the thickness of the snow cover in Stavropol. For the rest of the stations, there are no statistically significant trends.
in the change in the thickness of the snow cover. The construction and visualization of regional fields of seasonal variability of snow cover at the stations of the South of Russia were carried out using the geographic information system Surfer 6.0 [7]. For example, figures 1-4 show the SCT fields for the 1st decade (1st decade of October), 9th decade (3rd decade of December), 13th decade (1st decade of February) and 21st decade (3rd decade of April).

![Figure 1. SCT field (cm) in 1 decade (1st decade of October).](image1)

![Figure 2. SCT field (cm) in the 9th decade (3rd decade of December).](image2)

![Figure 3. SCT field (cm) in the 13th decade (1st decade of February).](image3)

![Figure 4. SCT field (cm) in the 21st decade (3rd decade of April).](image4)

To visualize the seasonal variation of SCT, graphs of model values of snow cover are plotted for 21 decades of the cold season (October-April) for each station. For a comparative analysis to the model of climatic norms and real data (readings) for 1960-2018 we have added the averaged SCT values for the last 10 years (2009-2018) at stations of different climatic zones (figure 5). Figure 5 shows the course of the SCT based on real data for 1960-2018 (readings, blue dots), according to the harmonic expansion model (model, red line) and the SCT course based on averaged real data for the last 10 years (counts, green triangles).
Figure 5. Graphs of model values for 1960-2018 SCT and average SCT values for 2009-2018.
Figure 5 a-d shows that over the past 10 years (2009-2018) there was an increase in the average ten-day SCT, especially in the first half of the cold season (from the 2nd decade of November to the 2nd decade of February), in the remaining decades the value SCT is close to the climatic norm (1960-2018).

4. Conclusions
The above results coincide with the conclusions we made in previous studies of snow cover in southern Russia [8-10]: against the background of global warming, the number of days with snow cover decreases, the dates of the Thus, an increase in the height of the SC is observed. Obviously, this is due to increased evaporation and an increase in water content in the atmosphere, leading to abundant both liquid precipitation and solid precipitation (snow).

The constructed regression model of seasonal variability of snow cover thickness in the south of Russia and adjacent territories of the Russian Federation makes it possible to use the results obtained in applications such as agricultural meteorology; climatology. The performed analysis of the seasonal variability of SCT allows us to make the following conclusions: the thickness of the snow cover for the southern regions of Russia has a pronounced seasonal variation with a coefficient of determination no worse than 55%. The fields of the parameters of the seasonal variation are quite smooth, and their variability is well physically conditioned. The results of the study are important for predicting crop yields in plane and foothill areas, and can also be used in tourist clusters of mountainous and high-mountainous regions of the Caucasus.

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