Present climate development in Southern Siberia: a 55-year weather observations record

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Abstract. Siberia is a key region for study of the climate development in north-central Eurasia in terms of global climatic change. The relief creates a major orographic barrier for atmospheric streams influencing the regional altitudinal weather zonality. Systematic 55-year (1963-2017) weather observations along the 700 km N-S latitudinal transect across the southern Siberian plains and the adjoining ranges of the Altai-Sayan Mountains document progressing seasonal temperature and humidity shifts. Standard meteorological data from twenty meteorological stations in different topographical and natural settings with specific weather conditions document a rise of a regional atmospheric humidity balance reflected by the increased bulk annual precipitation rates in the mountain areas accompanied by pronounced seasonal air-temperature fluctuations. This regionally trend provides evidence speaking in favor of the strengthening climate continentality over Siberia, which is also manifested by the pronounced seasonal temperature regime with increased thermally positive and negative air temperature anomalies. A landscape response to a climate warming is particularly evident in the high mountain zone. The present thermal conditions with raised MAT contribute to the progressing melting of mountain glaciers and degradation of permafrost in the alpine zone, as well as aridization of the parkland-steppe areas that are being partly transformed into continental semi-arid to deserted steppes. The associated environmental transformations trigger shifts in the local biotopes and ecosystems, with an altitudinal expansion of taiga-forest into the alpine tundra belt and xerothermic grassland invasions in the foothills. The modern climate changes have a major bearing to the Altai-Sayans socio-economic development.

1. Introduction

Weather dynamics reflecting dominant atmospheric circulation patterns in conjunction with regional topographical conditions plays the main role in the present climate formation and climate change over a particular territory, ultimately governing a functioning of natural environments as well as all aspects of the modern civilization. The goal of our studies in southern Siberia is to research a number of regional manifestations of climate trends for the last 55 years (the period of 1963-2017). These spatially encompass the northern plains and the southern mountain ranges of the Altai and Sayans.
Mountains (altitudinal gradient of 180-4000 m asl.). The unique location in the center of Eurasia characterized by a strongly continental climate regime underlines the fundamental relevance of the systematic weather observations in this particular strategic area.

This study summarizes results of meteorological observations on directions and rates of the present climate development over southern Siberia based on archival meteorological data for the period of 1963-2017 [1]. Implications of the weather-observations are of principal relevance in environmental management of the protected natural areas of southern Siberia and for the central governmental sustainable-development planning of the Gorny Altai and Tuva Republics, as well as in East Kazakhstan [2, 3].

The monitored territory encompasses the Altai and Sayan Mountains, which forms the main mountain system of southern Siberia adjoining the Mongolian Altai by the Tavan-Bogd-Ula massive (Naimandal Mt., 4374 m) and the Southern (Kazakh) Altai (3483 m) in the south (Fig. 1). This vast area of over 1 mil km$^2$ is characterized by a very diverse physiography. The Altai Mountains (Belukha Mt., 4506 m asl.) and the Western Sayan Mountains (3492 m) jointly create a major natural barrier delimiting the southern geographic limits of Siberia bordering the West Mongolian Altai, the Chinese Altai and the Southern Altai of East Kazakhstan. In the west, the continental topography gradually passes into the North Altai Plains (200-300 m asl.), representing the marginal parts of the West Siberian Lowland. The Western Sayans form the eastern continuation of the Altai Mountains, stretching for 500 km (89°-96° E). The Eastern Sayans extend 1,000 km from the Yenisei River at 92° E to the southwest end of Lake Baikal at 106° E.

![Figure 1](image1.png)

Figure 1. Geographical location of the study area in southern Siberia with the spatial and topographic distribution of the monitoring weather stations.

The present climate is strongly continental with major seasonal temperature deviations between the northern lowlands and the southern mountains. In winter, except for the highest elevations, climatic conditions in the mountains are generally less severe than in the open northern steppes, and a local microclimate prevails throughout the year in some protected locations in the Altai Mountains (the Upper Biya, Katun’, Chulyshman and the lower Chuya River basins) with a relatively thin snow cover during winter [3, 4, 5]. Annual temperatures as well as precipitation rates vary greatly, reflecting
particular topographic settings. Most of the annual precipitation falls on the W/NW slopes in the northern and central Altai, while the southern areas became more arid. In the Chuya Depression (1800-2000 m asl., Kosh-Agach), which is one of the most continental places in the Altai, an average July temperature is +25°C, whereas an average January temperature is -33°C, but it can occasionally drop to -60°C. Most of the local area is underlain by perennial mountain permafrost with an active thaw layer belong only 30-70 m thick. The lowland (200-500 m asl.) vegetation of southern Siberia is formed by the open steppe-parkland with mosaic birch-pine forests. Mixed taiga covers most of the foothill and the lower mountain zone (500-1500 m asl.), gradually passing at higher elevations (1500-2500 m asl.) into the alpine tundra with the Siberian pine, larch and dwarf birch. Semi-desert communities with an admixture of plant taxa characteristic of the Mongolian steppes are found in the upland depressions of the southern Altai.

2. Materials and Methods
This study summarizes results of investigations on present climate change in south-central Siberia delivered by 20 weather stations situated at different altitudes and specific topo-geographical conditions. The significance of this area is underlined by its unique position near a geographical center of Eurasia with a strongly continental climate regime and marked seasonal weather variations with low winter and high summer temperatures influenced by the Siberian cyclone/anticyclone atmospheric streams. The 20 state weather stations (WS) are positioned in diverse physio-geographic areas (of the Altai District, the Gorno Altai Republic, Khakassia, Buryatia and the Tuva Republic) following the territorial continental topographic gradient (180-4500 m asl.), providing regular daily measurements of standard atmospheric parameters (i.e. precipitation and temperature changes, wind-direction, atmospheric pressure, ground-frost and permafrost table). The analyzed summary databases include systematic meteorological data for the 1963-2017 periods.

The climate-change investigations encompass an extensive territory, geographically delimitated by 49°55' - 54°45' N and 82°10' - 99°49' E (the spatial position range of the weather stations). The N-S geographic transect of the monitored area runs over about 700 km through all the topographic and environmental zones from the northern steppe plains at the south-eastern margin of the West Siberian Lowland, across the Altai-Sayan foothills, and the low-, mid-, and high-mountains, representing the principal mountain ranges of southern Siberia adjacent to the Kazakhstan-Chinese-Mongolian boarder. The corresponding continental relief gradient rises from 183 m asl. (Barnaul WS) to 2600 m. asl. (Kara-Tiurek WS), accounting for a total of 2417 m of the vertical regional elevation difference.

3. Weather Monitoring Results
In dependence of the dominant regional climatic conditions, the thermal regime of the mountain areas is significantly differentiated. The mean seasonal winter temperature varies from -5 to -27 °C. In the low-mountain areas and foothills, a mean July temperature is around 16-19 °C, 12-15 °C in the mid-mountain zone, and 13-21°C in the basins and depressions; in the high-mountain zone it drops to 6 °C.

A maximum amount of precipitation falls on the NW slopes exposed to atmospheric stream fronts; the minimum precipitation rates in the arid intermountain basins are enclosed by mountain ranges and in other precipitation-shadowed geomorphic locations [6, 7, 8].

A gradual rise of mean annual air temperature is observed from the late 1960s and especially after 1976. A minimal MAT rise has been documented at the weather stations Kara-Tiurek, Ak-Kem, Oleniya Rechka in the high mountain areas of southern Siberia (the Western Sayans and Gorno Altai Mnts.), on average 0.2-0.3°C/10 years, whereas a maximum progressing climate warming is in the major inter-mountain depressions (Kosh-Agach, Erzin, Kyzyl and Toora-Khem) on average 0.4-0.6°C/10 years. Numbers of frost-free days are also increasing with the strengthening trend of climate continentality (Fig. 2).
Figure 2. Increased temperature rate in respect to the MAT at the monitored locations (weather stations, A) following the topographic gradient from the northern plains to the southern mountain regions for the 55 year observation period (1963-2017), Altai-Sayans Mnts (Altai-Sayan) and continental/mountain basins (B).

According to the mid-seasonal air temperature rates, the monitoring southern Siberian meteorological weather stations (WS) can be grouped into three zones: (a) 1st zone (SMAT 15-20°C): plains, foothills, low-mountains (500-1000 m asl.) and the inter-mountain basins; (b) 2nd zone (SMAT 10-14°C) of the mid-mountain areas (1000-2000 m asl.); (c) 3rd zone (SMAT 2-9°C) of the high-mountain areas (2000-4000 m asl.), with the highest values (8-9°C) at the Ak-Kem WS (2050 m asl.) and (5-7°C) at the Kara-Tiurek WS (2598 m asl.). A long-term (55-year) rise of the SMAT values across all geographical zones is only 0.5-1.0 °C except for slightly the higher values (2.0-2.2°C) in the mountain basins of Gorno Altai and Tuva (Fig. 2, 3).
Figure 3. The variability of annual precipitation, Kara-Tiurek (2600 m, Katunsky range of Altai) and Kyzyl (626 m, Tuva intermountain basin), 1966-2017: linear trends and 10-year moving averages.

4. Discussion
Comparative analyses of the historical and the present meteorological databases provide eloquent evidence on the changing climate in southern Siberia with the trend of a strengthening continentality. Despite the significant interannual precipitation variability, a little reduction of the annual total has been observed in the Altai in 1963-2017 (Fig. 3). The mean seasonal temperature values across the monitored territory based on the 55-year observations show a differential rise by ca. 3.5 °C in winter, 1.6 °C in spring, 1°C in summer, and 0.9 °C in autumn. This seasonal temperature trend unequivocally documents a progressing climate warming in the inner Eurasia in agreement with biotic and glacial records from the Altai and Sayan Mountains [5]. This atmospheric dynamics is clearly expressed by the current environmental transformations that have direct effects on functioning of the southern Siberian ecosystems. The reported results on the present climate change in the broader Altai–Sayan Eco-Region corroborate the precipitation increase trends in the mountain areas and, on contrary, the progressing rates of aridization and desertification in the lowland steppe regions as well as in the intra-mountain basins of the southern Altai area [8].

The Altai-Sayan Eco-region that constitutes the major part of the investigated southern Siberia belongs to the most pristine natural areas in the mid-latitude boreal forest belt of Eurasia. This environmentally unique territory in the Russian-Mongolian-Kazakh border zone (Fig. 1) includes several major national parks and nature reserves. The present parkland-steppe and mountain ecosystems of southern Siberia experience progressing environmental transformations and ecology degradations as a result of the complex processes trigged by the present global climate development. The related changes in natural (bio- and geo-) environment affect the wide mosaic of parkland-steppe, foothill and mountain ecosystems and biotopes, hosting a number of endemic and/or elsewere rare species of flora and fauna that are subject of national and international protection. Hence, systematic monitoring of the regional climate is of utmost relevance. Raising summer temperatures also contribute to the regional aridization, the mountain permafrost degradation and to an accelerated ablation of the retreating alpine glaciers, reaching a maximum rate up to 20 m per year on the Southern Altai Range [8].

5. Conclusion
The results of the 55-year (1963-2017) systematic meteorological observation in the Altai and Sayan region display significant both annual and seasonal temperature and humidity variations with a definite trend of climate warming corroborating the present climate change in the continental Eurasia, particularly winter and spring mean air temperatures have significantly increased. A minimal MAT rise is in the high mountain areas, whereas the maximum progressing climate warming has been
observed in the inter-mountain continental depressions. The meteorological data also indicate an increase of regional humidity reflected by the bulk annual precipitation rates in the foothills and the mountain areas. In places of the higher topographic relief, the moisture regime and atmospheric circulation dynamics is being accentuated.

This definite climate-change trend has been recorded in conjunction with the related natural transformations throughout the entire southern Siberian territory as manifested by the expansion of grasslands in the foothills and by the rise of tree-line in the alpine mountain zone. Raising annual temperatures trigger a progressive melting of glaciers, a localized degradation of the mountain permafrost in the alpine zone (> 2,500 m asl.). The associated ecological processes include shifts in the mountain biotopes: an expansion of boreal taiga forests (now with limits at 2100-2300 m asl.) into the alpine tundra zone, a geo-botanical restructuring of xenotheric alpine meadows and concomitant biological changes in behavior of some fauna species, such as earlier arrival and a later departure of migratory birds for nesting. On the contrary, a progressing aridization of the mountain parkland-steppe areas due to the strengthened continental climate regime with high solar radiation with increased number of sunny days and a precipitation decline lead to a gradual transformation into semi-arid parkland steppes and semi-desertic steppes [9].

The implications resulting from the historical and present meteorological data analysis as well as the climate change proxies can be eventually used in the assessment of the ongoing and future climate change feedbacks to the southern Siberian environments with implications to management of natural resources, biodiversity protection and the present/perspective sustainable socio-economic development, with an optimal planning of exploitation of natural resources. The present climate change-linked economic effects may, on long-term, positively promote production in agriculture and forestry over the monitored territory due to ameliorated weather conditions and expansion of arable lands and taiga forests, respectively. On contrary, a complex evaluation of the main natural climate-triggered risks (including soil cover erosion, desertification and industrial resource exploitation) can ultimately contribute to establishment of an integrated concept of effective nature protection strategies in the Altai and Sayan Eco-Region, and an environmental hazard monitoring related to present climate change.

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