Spatial year-ahead forecast of air temperature and precipitation in large mountain areas

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Abstract

The method for spatial reconstruction of monthly mean air temperature and monthly precipitation is proposed for large mountain areas. Meteorological factor dynamics is described in percent of long-term monthly average values measured “in situ”. It is almost independent of height, exposure and climate of characterized sites and remains the same throughout the mountainous territory. By the example of the Altai-Sayan mountain country covering more than 2,500,000 km², we averaged (spatially generalized) the data of 11 weather stations and obtained the country’s long-term dynamics of monthly mean air temperature and monthly precipitation for 1951–2016. Using a simple moving average of 6–7 recent years of stations observations, we provide a reliable year-ahead prediction of a factor value for any spot of the country without additional data. Modification of RSR and Nash–Sutcliffe efficiency indices is proposed to correct their shortcomings in assessing the quality of various predictive methods and models. The developed method of four-season weather forecast has the quality close to the theoretically best for statistical forecasts.

Keywords Weather · Air temperature · Precipitation · Forecast · Mountains

1 Introduction

In large mountain regions, the influence of the underlying surface on regional and local atmospheric processes is very substantial. It manifests itself as the decrease in temperature with altitude, significantly different precipitation on the windward and leeward mountain slopes, the increase in precipitation with altitude along the slopes, the formation of lee vortices and mountain waves, and other orographic effects [1]. As a result, a complex vertical and horizontal differentiation of mountain meteorological fields is formed. The analysis of these fields is laborious and often unfeasible because of few weather stations existed. The scarce observational data in turn cannot ensure reliable long-term weather forecasts, which are necessary for bulk of human affairs in mountain regions [2].

Nowadays, a large number of empirical-statistical and deterministic methods for long-term weather and climate

forecast and their combinations are proposed [3–6]. The first are based on statistical regularities of atmospheric processes and require the longest and homogeneous meteorological data series (e.g., [7]), whereas the second—on physical laws of atmospheric or atmospheric–oceanic processes described by rather complicated equations as, for example, in the mesoscale model WRF [8, 9]. The current mainstream in the mountain climate research is the detailed elaboration of the multiscale numerical models for weather and climate forecast [10]. It requires accurate measurements of 3D meteorological fields (of temperature, precipitation, wind, pressure, humidity, etc.), orographic characteristics and, therefore, numerous measurement instrumentation. For large mountain areas, it would not do. In this paper, we present an effective methodology for the reconstruction and forecast of monthly mean air temperature and monthly precipitation with a year lead time, which can be applied to large mountain territories

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and based on minimum data sets in contrast to the methods mentioned above.

We have developed and statistically justified the method for spatial generalization/averaging monthly mean temperature of the surface air layer and monthly precipitation to ensure the adequate assessment of their temporal dynamics throughout the mountainous territory [11]. The developed technique was successfully used in mountain river models of high quality for hydrological and hydrochemical calculations under scarce meteorological data [12–14]. In the present study, it serves as the basis for the statistical method of spatial forecasting of temperature and precipitation to be used for calculations of mountain river runoff (for example, spring–summer flood) at insufficient meteorological observations.

2 Source data and methodology

Our investigation deals with the Altai-Sayan mountain country located between 50–56° N and 82–90° E. This country covers more than 2,500,000 km² and represents a part of the world watershed between the humid region

of the Arctic Ocean and the arid drainage one of Central Asia. It also serves as the catchment for the Siberian large rivers as the Ob and the Irtysh distinguished by a complex hydrographic network. Its territory includes the Mountain Altai and partially the Salair Ridge with Kuznetsk Alatau and the adjacent plains. The ridges height of the mountain systems reaches mostly 2000–2500 m, and 3500–4500 m in the Mountain Altai. Various climatic conditions and diversity of landscapes (glacial-nival, tundra, Alpine and subalpine meadows, forest, steppe and semi-desert) are a special feature of the Altai-Sayan mountain country [15]. For instance, annual amount of precipitation varies very widely: the northern slopes at altitudes over 3000 m get 1200–2500 mm of precipitation per year, the middle parts of the slopes—up to 600 mm and the bottom—about 200 mm.

We use the data on monthly mean temperature of the surface air layer and monthly precipitation from 11 reference weather stations. Observations started in 1951 and are still in progress (Fig. 1, Table 1) [16, 17]. It is assumed that meteorological factors depend on the same macro- and mesoscale of atmospheric heat and moisture circulations [18]. Long-term average temperature and precipitation for the whole

Fig. 1 Location of 11 reference weather stations, the data of which were used to calculate dynamics of air temperature and precipitation throughout the Altai-Sayan mountain country

Table 1 Geographical characteristics of selected reference weather stations

Weather station	WMO index	Latitude	Longitude	Altitude, a.s.l, m
Biysk-Zonal ^a	29939	52° 41′	84° 56′	222
Zmeinogorsk ^b	36038	51° 09′	82° 10′	354
Kamen'-na-Obi ^a	29822	53° 49′	81° 16′	127
Kara-Tyurek ^b	36442	50° 02′	86° 27′	2601
Kuzedeevo ^c	29849	53° 20′	87° 11′	293
Kyzyl-Ozek ^b	36055	51° 54′	86° 00′	324
Rebrikha ^a	29923	53° 05′	82° 20′	218
Slavgorod ^a	29915	52° 58′	78° 39′	125
Soloneshnoye ^b	36045	51° 38′	84° 20′	409
Ust-Koksa ^b	36229	50° 16′	85° 37′	977
Yaylu ^b	36064	51° 46′	87° 36′	482

^aPlains adjacent to the Mountain Altai^bMountain Altai^cKuznetsk intermountain basin

territory of the mountain country are given in Table 2. More detailed statistical characteristics of these factors can be found in [19].

According to the spatial generalization method, monthly air temperature and precipitation for each year are converted into percent relative to their long-term in situ average for a normalization month [11, 20]. Using “in situ” values let us to reduce the influence of local climatic and topographic features. In winter, due to radiative cooling the air goes along the mountain slopes down to the basin bottom. This leads to temperature inversions with vertical gradients reaching 0.5 °C/100 m [21]. Despite such changes in temperature with height, its relative values remain the same throughout the country. In the warm period with the summer type of atmospheric circulation, temperature inversions do not occur and its relative values remain stable again. Consequently, we can obtain the uniform monthly and interannual dynamics of meteorological factors throughout the mountain country [11].

We use January as the normalization month for the cold period of the year and July for the warm one. These months give the least standard deviation of relative air temperature series for each of 12 months for all 11 reference weather stations. In such a manner, July gives the least standard deviation of relative monthly precipitation series throughout the year. The spatial generalization, i.e. averaging the data across 11 stations for each month and year, gives the unified monthly dynamics of relative values of temperature

and precipitation that is needed for adequate reflection of meteorological situation in any part of the mountain country and adjacent plains (Table 1). It makes possible to calculate the dynamics of water and hydrochemical runoffs from 34 river basins of the Altai-Sayan mountain country with a good accuracy in the absence of meteorological observations in the basins [12–14].

It is worth noting that more than tenfold changes in precipitation with height along a mountain slope *do not allow the direct use of low-resolution reanalysis data* on the Altai-Sayan mountains. Applying high-resolution regional methods/models for reanalysis downscaling to 10 km or close to it (e.g., [22, 23]) is also useless due to insufficient meteorological observations. In contrast, the developed assessment of air temperature and precipitation dynamics can be easily applied in GIS technologies and the reanalysis as well. To do this, just divide the available meteorological data by their long-term average in situ values for January and July and spatially generalize them to obtain the adequate description of factor dynamics throughout the mountain area. In order to restore the long-term dynamics of factors in terms of °C and mm, one should know their monthly values for January and July at the study site for several years. First, the observed and relative values are used to calculate the transition coefficient. Then, the calculated long-term dynamics of both relative monthly temperature and precipitation is multiplied by their coefficients.

Table 2 Annual mean values of air temperature and precipitation for the study area (1951–2016)

Climatic characteristic	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
Temperature, °C	−16.1	−14.7	−7.7	2.6	10.4	15.8	17.8	15.4	9.6	2.1	−7.2	−13.3
Precipitation, mm	21.7	19.5	22.9	40.6	59.4	70.6	83.5	72.5	50.1	51.0	41.0	30.3

We try to find the best forecast of the relative values of monthly mean air temperature and monthly precipitation for next year (from 1984 to 2016) by using their averages over preceding 1, 2, 3, ..., 33-year moving periods (cf., [24]). To calculate the latter, we use the derived unified monthly and interannual dynamics for 1951–2016 throughout the Altai-Sayan mountain country ($65 \times 12 = 780$ relative values of temperature and 780—precipitation). It is expected to apply this forecast in hydrological models, the accuracy of which is usually estimated via RSR and NSE indices. RSR stands for RMSE-observation Standard deviation Ratio, where RMSE is root-mean-square error [25, 26]. NSE stands for Nash–Sutcliffe model Efficiency [25]. Obviously, to characterize the accuracy of our forecast, it is advisable to use a criterion similar to RSR and NSE [11]:

$$A = S_{\text{diff}} / \sqrt{2} S_{\text{obs}}, \quad (1a)$$

where A is the forecast accuracy, S_{diff} is the standard (mean square) deviation of residuals (the difference between the corresponding values of the predicted and the observed data series), S_{obs} is the standard deviation for the observed series, and multiplier $1/\sqrt{2}$ makes up a standard range 0–1 involving two meaningful intervals of A values.

With the use of several-year moving averaging for the forecast, the average values of the predicted and observed series will be almost the same. The simple average of residuals (constant overestimation or under-statement of prediction) will be negligible compared to S_{diff} . Statistical averages of meteorological factors over 1, 2, 3, ..., 33-year moving preceding periods can hardly correlate with their actual fluctuations in the projected years. Hence, in accordance with the variance sum law, $(S_{\text{diff}})^2$ includes only two summands:

$$(S_{\text{diff}})^2 \approx (S_{\text{pred}})^2 + (S_{\text{obs}})^2, \quad (1b)$$

where S_{pred} is the standard deviation for the predicted series of 1984–2016.

According to Eqs. (1), criterion A can vary from zero to one or more:

- close to 0 means the series identity and the “absolute” accuracy of deterministic forecast;
- $\sqrt{(S_{\text{pred}})^2 + (S_{\text{obs}})^2} / \sqrt{2} S_{\text{obs}} = 1/\sqrt{2} = 0.71$ —the threshold at which the predicted statistically average values of a meteorological characteristic are equal to the actual average for the projected years with $(S_{\text{pred}})^2 = 0$, thus being *the best statistical forecast*. It should be emphasized that we define the accuracy at $A = 0.71$ as consistent with *the average for future values* of projected characteristics. Therefore, such an

accuracy is the best statistical forecast for the year-ahead statistical prediction;

- close to 1—at zero covariance, series variances are the same; here the forecast method is equivalent to random variations of a characteristic around its average with the variance corresponding to the observed series; the method of random variations is often used in mathematical models to create a “natural” spread of values of input meteorological factors;
- more than 1—at zero covariance, the variance of the calculated series is greater than that of the observed series; therefore, this forecast method is impractical.

The expression (1a) shows that criterion A is similar to the normalized error in the predictive methods. For normalization, not the average characteristic but the standard deviation of observations (S_{obs}) from this average is used. The interval $A = 0.71$ –1 characterizes different adequacy of the characteristic predicted with the use of several-year statistical average and its observed values (prediction is the best at $A \sim 0.71$).

Criterion A is the rescaling of RSR and NSE model quality indicators related with A through $\text{RSR} = A\sqrt{2}$ and $\text{NSE} = 1 - \text{RSR}^2 = 1 - 2A^2$. As before in Eq. (1b), for reliable mathematical models and forecasts, the simple average of residuals between the predicted and observed data can be considered equal to zero because of its smallness as compared to S_{diff} . Compared with RSR and NSE, the range of A application is wider due to extra assessment of statistical weather forecasting.

We deal with $(12 \text{ month}) \times (33 \text{ years}) \times (11 \text{ weather stations}) = 4356$ values of monthly mean temperature and the same amount of monthly precipitation, which serve as the observation data sets for verification of the presented methodology. Obviously, these sets are sufficient for reliable statistical estimates of the year-ahead forecast quality by criterion A and its benchmark 0.71. Hence, there is no need in using extra statistical characteristics (correlations and similar ones) and verification methods.

3 Results and discussion

To analyze the results of spatial statistical forecasting, we specify four periods/seasons reflecting peculiar characteristics of the weather and hydrological situation in the Altai-Sayan mountain country: the first (winter period, XII–III months), the second (spring–summer flood, IV–VI), the third (summer, VII–VIII) and the fourth (autumn, IX–XI) [12]. In this case, criterion (1) is calculated for individual months of the year with further averaging over the season. This significantly improves the evaluation of the proposed

method as compared with the direct prognostic assessment of seasonal or annual averages [27].

Figures 2 and 3 show criterion A for the year-ahead forecast of relative monthly air temperature and precipitation in each season. A depends on the duration of moving periods preceding the prediction years and is used for calculating the moving several-year averages of characteristics. We carried out the forecast for each of 11 reference weather stations using the spatially generalized data of the rest ten ones. Thus, we checked the forecast feasibility in any point of the Altai-Sayan mountain country regardless of local climatic conditions, topographic differences and landscapes.

Figures 2 and 3 suggest that criterion A characterizing the quality of four-season forecast is improved rapidly with an increase in the moving averaging period; at 6–7 year duration of this period, criterion A approaches its best value ~ 0.71 . With further increase in the averaging period, criterion A stabilizes and makes up for temperature 0.74, 0.73, 0.78, 0.73, and for precipitation—0.73, 0.73, 0.72, 0.73 for 1, 2, 3, 4 seasons, respectively. Thus, the use of observation data for 6–7 years obtained from several reference weather stations provides a reliable prediction. The nearness of A values to 0.71 also confirms the adequacy of the spatial generalization of meteorological factors; in the absence of this adequacy, A should be significantly greater than 0.71. Note that the predicted values of monthly air

temperature and precipitation vary significantly from year to year and *do not coincide with the long-term meteorological averages*, the calculation of which requires a 30-year period [28] or even longer one (50–80 years) [29].

We can try to calculate the model quality indicator NSE considered above. Using the average optimal criterion $A = 0.74$ (Figs. 2, 3), we obtain $NSE = 1 - 2A^2 = 1 - 2(0.74)^2 = -0.1$. NSE less than 0.50 is unsatisfactory [25] and, therefore, unsuitable for assessing the statistical forecast quality.

4 Conclusions

1. The relative changes in monthly mean air temperature and monthly precipitation calculated via their normalization (conversion into percent relative to their long-term in situ average for the normalization month) and spatial generalization (averaging across several reference weather stations) have uniform monthly and interannual dynamics throughout the Altai-Sayan mountain country and adjacent plains. Their dynamics is practically independent of spatial coordinates and the decrease/increase in temperature/precipitation with altitude along mountain slopes. For transition to their generally accepted units ($^{\circ}\text{C}$, mm), one

Fig. 2 Forecast quality A for moving several-year averages of monthly mean air temperature for four seasons: XII–III (a), IV–VI (b), VII–VIII (c) and IX–XI (d) months. A depends on the number of years in averaging period preceding each prognostic year (1984–2016)

Fig. 3 Forecast quality A for moving several-year averages of monthly precipitation for four seasons (see notations in Fig. 2)

should know long-term average January and July temperature and July precipitation for the study site. The developed procedure can be easily applied in GIS technologies and high-resolution regional reanalysis as well.

2. To predict four-season weather for the year ahead, just 6–7 recent years of meteorological observations are needed. Due to normalization and spatial generalization of monthly mean air temperature and monthly precipitation, their predicted percentage values are valid throughout the Altai-Sayan mountain country exceeding the area of 2,500,000 km².
3. The universal version of RSR and Nash–Sutcliffe Efficiency indices is proposed to estimate the quality of various predictive methods and models. The quality of the developed statistical method for the spatial year-ahead meteorological forecast in mountain areas is close to the theoretically best one.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests

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