Applicability of reanalysis data to diagnosis of snow avalanches in the Caucasus Mountains

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Applicability of reanalysis data to diagnosis of snow avalanches in the Caucasus Mountains

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Abstract. This work is devoted to assessing the use of reanalysis data for diagnosing the danger of avalanches using the Caucasus Mountains as an example. This method is applicable to entire mountain regions, not individual slopes, and uses the results of both observations and numerical modeling in the atmosphere. A comparison of observational and reanalysis data of Era-Interim, CFSR, and NCEP-NCAR is performed based on a classification of winters by using air temperature and precipitation data to assess avalanche hazard. The accuracy of the temperature and precipitation data and their influence on avalanche hazard are analyzed.

1. Introduction
Snow avalanches are a widespread natural phenomenon that significantly complicates the economic development of mountainous regions and poses a threat to human life. This determined the need for a detailed study of the conditions of loss of stability of snow masses on mountain slopes, the origin and movement of avalanches, the development of methods for predicting avalanche danger, and improving the methods of protection against avalanches. A snow avalanche is a dangerous glaciological phenomenon and, thus, not only its operational forecast, but also projection of the future climate changes would be of interest. Climate change scenarios can be used to determine future avalanche characteristics. For example, the avalanche characteristics in the Kamchatka mountains and Tien Shan were calculated [1], and the avalanche activity decreasing by the middle of the 21st century for Kamchatka and increasing in Tien Shan was shown. When assessing the avalanche danger throughout the world [2], general patterns were revealed: in the continental little snow mountain regions the avalanche activity decrease is expected, in contrast to snowy mountains.

In particular, for the Caucasus, the snow cover thickness decrease (by more than 30 cm), the recurrence of avalanche situations, and the duration of the avalanche-dangerous period are predicted [3]. The Caucasus is part of the southern mountain belt characterized by 3 avalanche genesis types: fresh snow, snow slabs, and advective process.

The characteristic features of this area are a large amount of precipitation and the snow cover thickness averaging 1-3 meters, the heterogeneity of the precipitation field, relatively cold winters, however, with a high frequency of intense and prolonged thaws, mountain-valley circulation (foehn effects), and snow drift. The Central Caucasus region is most densely populated, and the tourism sector has been actively developed in it over the past decades. This necessitates monitoring and forecasting the avalanche danger in the region.

An important role in the avalanche formation is played by circulation factors that determine the temperature and precipitation regime. To identify the circulation factors contributing to the occurrence of avalanches, the avalanche events were compared with various circulation indices [4]. The division
into elementary circulation mechanisms (ECMs) by B.L. Derzievsky [5] is widely used. For Caucasus, heavy precipitation in winter most often occurs during ECMs 13s, 8gs, 11a, and 12a [6]. Such a configuration of atmospheric processes corresponds to the emergence of a Mediterranean cyclone on the Black Sea and its blocking by an anticyclone in the south of the European territory of Russia, which additionally increases the precipitation. There are also other indices that have a significant impact on the circulation of the atmosphere in the European territory of Russia. In [7], correlation analysis was used to analyze the relationship of some indices with the temperature and precipitation in the Teberda Reserve and other stations in the North Caucasus region.

In paper [8], a simple statistical ratio between the air temperature-precipitation parameters and the avalanche danger during the cold period is presented. This method allows, among snowy winters, to establish those seasons that are accompanied by massive catastrophic avalanches. The classification is based on a correlation matrix principle, according to which its winters were divided into four groups (in terms of temperature conditions and moisture supply): by air temperature: A - abnormally warm (t1); B - moderately warm (t2); B - moderately cold (t3); G - abnormally cold (t4); by precipitation: 1 - abnormally dry (x1); 2 - with a deficit of precipitation (x2); 3 - with precipitation above normal (x3); 4 - abnormally moist (x4). Deviations are calculated with the mean seasonal temperature value (the sum of precipitation for the season) and the standard deviation of this value. The ratio of hydrothermal conditions in the matrix determines 16 possible types of winters (Figure 1).

The authors draw attention to the predominance of winters with little snow in the last 6 years, which they associate with an increase in the blocking anticyclonic situations over the Caucasus mountains.

2. Materials and methods
To calculate the avalanche danger, meteorological reanalyses of different generations was used (Table 1).

<table>
<thead>
<tr>
<th>Reanalysis name</th>
<th>Time period</th>
<th>characteristic of grids</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCEP-NCAR</td>
<td>1948-now</td>
<td>2.5° x 2.5°</td>
</tr>
</tbody>
</table>
| CFSR/CFS          | 1979-2010/2010-now   | Temperature: 0.312° x ~0.312°/ 0.205° x ~0.204°  
|                   |                      | Precipitation: 0.5° x 0.5° |

Figure 1. Identification of avalanche-dangerous winters in the Caucasus (1936-1987) according to [8]: A - abnormally warm; B - moderately warm; B - moderately cold; G - abnormally cold; numbers in circles: 1 - abnormally dry; 2 - with a deficit of precipitation; 3 - with precipitation above normal; 4 - abnormally moist; avalanche danger of winters: 1 - weak; 2 - medium; 3 - strong; 4 - abnormally strong.
To assess the feasibility of using reanalysis data for such tasks in the mountainous region, a comparison was made with the actual observational data at the Vladikavkaz, Zelenchugskaya, Kislovodsk, Klukhorskiy Peregul, Krasnaya Polyana, Sochi, Shatzhatmaz, and Sulak stations (Table 2).

**Table 2. Weather stations characteristic.**

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Height above sea level, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>37228</td>
<td>Vladikavkaz</td>
<td>43.03</td>
<td>44.68</td>
<td>702</td>
</tr>
<tr>
<td>37112</td>
<td>Zelenchugskaya</td>
<td>43.87</td>
<td>41.57</td>
<td>928</td>
</tr>
<tr>
<td>37123</td>
<td>Kislovodsk</td>
<td>43.9</td>
<td>42.72</td>
<td>943</td>
</tr>
<tr>
<td>37196</td>
<td>Klukhorskiy Peregul</td>
<td>43.25</td>
<td>41.83</td>
<td>2037</td>
</tr>
<tr>
<td>37107</td>
<td>Krasnaya Polyana</td>
<td>43.68</td>
<td>40.2</td>
<td>564</td>
</tr>
<tr>
<td>37099</td>
<td>Sochi</td>
<td>43.58</td>
<td>39.77</td>
<td>142</td>
</tr>
<tr>
<td>37461</td>
<td>Sulak</td>
<td>42.37</td>
<td>46.25</td>
<td>2927</td>
</tr>
<tr>
<td>37126</td>
<td>Shatzhatmaz</td>
<td>43.73</td>
<td>42.67</td>
<td>2070</td>
</tr>
</tbody>
</table>

To compare the reanalysis data with the weather stations, the values at the reanalysis grid-points were interpolated into the points of meteo stations (with the station coordinates); the linear interpolation method was used. The temperature value was converted from the gradient of the standard atmosphere (0.65 °C/100m) to the actual height of the weather station. We calculated the average errors of the seasonal values and the correlation coefficients between the data on air temperature and the amount of precipitation for the cold period (Figure 2). This result is in good agreement with the assessments of the quality of reanalyses in the mountains carried out in [9, 10, 11]. According to the temperature data, more than a half of the stations have a high correlation coefficient, the exceptions are the highest stations (Klukhorsky Peregul and Terskol) and Sochi. Most likely, the local orographic effects (temperature changes associated with the orientation of slopes, convex and concave landforms) play a decisive role at these stations. The Era-Interim reanalysis always reproduces the temporal dynamics of temperature better, but the average error for it and the CFSR is, on average, the same. The NCEP-NCAR reanalysis has the largest error value.
The correlation coefficients of precipitation are much lower (only a few points with \( r \geq 0.6 \)). The temporal variability was most similar at the Sochi station. The error of the values of the sum of seasonal precipitation as a percentage of the annual sum was also calculated. It varies from 2 to 44.3\%, but at most stations it does not exceed 30\%, which is quite good for a mountainous area. The worst reproduction is the precipitation totals at the Shatzhatmaz station.

3. Results

Let us analyze the degree of avalanche danger according to the reanalysis data. In the Greater Caucasus, winters with extreme avalanches were observed in 1953-1954, 1955-1956, 1967-1968, 1971-1972, 1975-1976, 1986-1987, 1988-1989, and 1992-1993 (statistics are presented from 1951 to 1993). According to Oleinikov’s classification \[8\], when calculating the degree of avalanche danger in these winters, 4 of them fell into the gradation very strong, and 2 - strong. The same calculations were carried out for all three reanalyses, and a comparison was made with the results for the Terskol meteorological station. It should be noted that according to the results of calculations based on reanalysis in the last 20 years, 4 degrees of avalanche danger have practically not been observed. Thus, in the last 20 years we have seen a decrease in the number of extreme avalanches.

Let us consider in more detail the comparison of the avalanche hazard indicator according to reanalyses with the data of meteorological observations (Figure 3). Most often the degree of avalanche activity is the same for both types of data. For NCEP-NCAR data we have no more than a two-category discrepancy, unlike the other reanalyses. It can be noted that NCEP-NCAR data based on calculations overestimate the avalanche danger most often, while the CFSR, on the contrary, often underestimates it (but to a lesser extent). No such regularities were found in the Era-Interim reanalysis.

According to preliminary results, winters with a large number of catastrophic avalanches were associated exclusively with the below-zero temperature anomaly at heights of 850, 700, and 500 hPa.
Since the middle of the 20th century, a decrease in the integral moisture content in the air column has been observed, while catastrophic avalanches were associated precisely with a negative moisture content anomaly (Figure 4b).

Figure 4. Temperature anomalies relative to climatic norms at 850 hPa (a) and moisture content anomaly in the air column (b) for the Caucasus region.

4. Conclusions
We showed that reanalysis data can be used to estimate the characteristics of avalanche hazard at least qualitatively. The reanalysis data can give an avalanche danger assessment in the Caucasus Mountains with acceptable accuracy. No large deviations of the NCEP-NCAR data from observations have been observed. A decrease in the number of winters with extreme avalanches over the past 20 years due to an increase in the frequency of warm winters has been observed. A key factor in the occurrence of extreme avalanches in the Central Caucasus is the temperature: the strongest avalanche events have occurred against the background of deep negative temperature anomalies, but not positive anomalies of the atmospheric moisture content.

Acknowledgments
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