Estimating Volume Change of Mountain Glaciers Using SRTM and Map-Based Topographic Data

Arzhan B. Surazakov and Vladimir B. Aizen

Abstract*—This paper describes a method for estimating the volume change of mountain glaciers using the Shuttle Radar Topography Mission (SRTM) C-band data (2000) and a digital elevation model (DEM) generated from topographic maps. This approach was developed with SRTM data and topographic maps of 1 : 25 000 scale (1977) from the Akshiirak glaciers (Tien Shan, Central Asia). The DEM for 1977 was generated using 10-m contour lines from 18 map sheets covering the Akshiirak massif and surrounding area. The nominal vertical accuracy of the maps is 3.3 m. The standard deviation of the differences between the map-derived DEM and the SRTM data on glacier-free areas of less than 25° is 6.3 m. A single localized region in the western periphery of the study area with systematic error in the SRTM data from -20 to 12 m on a 30-km spatial scale was found and excluded from the error analysis. Assuming a 10-m map error on the upper snow-covered glacier areas, the estimated root-mean-square error of the glacier surface change is 8.2 m. From 1977 to 1999, the average glacier surface thinning is 15.1 m, and the estimated volume loss is 6.15 km^3. The rate of the Akshiirak glacier volume loss has increased by 2.7 times, compared with historical data from 1943 to 1977. The SRTM data show an opportunity for quantifying climatic and dynamic surface elevation changes in mountain glaciers. Ice, Cloud, and land Elevation Satellite (ICESat) laser altimetry and SRTM data could also be used for the estimation of short-term surface changes of mountain glaciers.

***Index Terms*—Error analysis, glaciers, remote sensing, terrain mapping, volume measurement.**

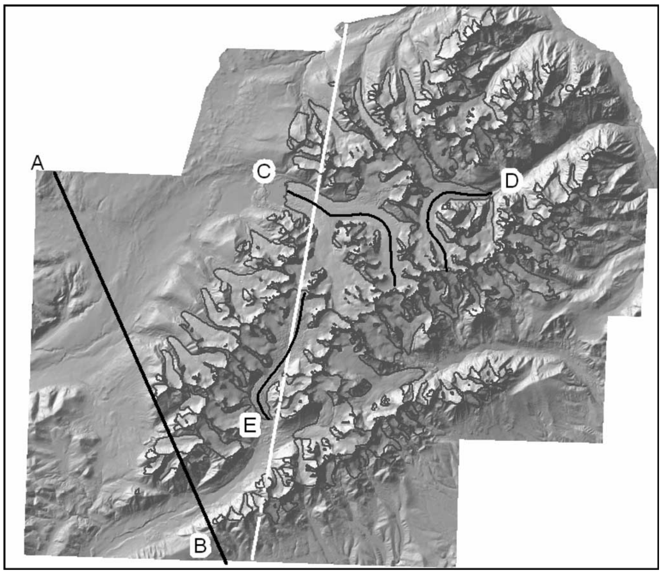

Fig. 1. Akshiirak glaciers and the DEM 1977. Line AB approximately separates the area with the systematic error in the SRTM data shown in Fig. 2. Glacier surface change profiles C, D, and E are shown in Fig. 3. White discrete line is an ICESat ground track acquired on October 30, 2003.

I. INTRODUCTION

ESSENTIAL parts of the ongoing glacier monitoring initiatives (World Glacier Monitoring Service, Global Land Ice Measurements from Space) are the regional and global glacier inventories that were developed using satellite remote sensing techniques [1], [2]. However, the traditional planimetric indicators of glacier change, such as area and length, though readily available from optical imagery, do not take into account possible changes in glacier thickness. Several recent studies have shown successful application of airborne laser altimetry [3], [4] and satellite photogrammetry [5] for measuring glacier thickness change. With these techniques, however, the necessity of extensive field work for laser altimetry and problems of digital elevation model (DEM) generation on featureless snow fields using satellite photogrammetry limit the widespread use for glacier monitoring in remote alpine areas.

The Shuttle Radar Topography Mission (SRTM) (February 11–22, 2000) resulted in a global DEM of land area between 60° N and 54° S. The nominal vertical accuracy is 6 m relative and 16 m absolute, and the nominal horizontal accuracy is 15 m relative and 20 m relative (90%) [6]. Consistent methodology, coverage, and accuracy of the SRTM data provide a global "snapshot" of the land surface, and therefore, it could be used as a reference point for local and regional glacier volume change studies [7], [8] and global comparisons.

Another source of global elevation data is Ice, Cloud, and land Elevation Satellite (ICESat) altimetry [9]. The accuracy of the narrow-beam laser altimetry is at the decimeter level. The mission has been designed primarily for measurements of polar ice sheet volume changes [10]. However, ICESat data have also been used for measurements of mountain glaciers [11]. We used ICESat and SRTM data for estimating the modern rates of glacier surface change.

Here, we present methods, results, and accuracy estimations for deriving glacier surface and volume changes on the Akshiirak massif using SRTM and ICESat data, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images, and topographic maps.

The Akshiirak massif is located in the central part of the Tien Shan, 41.9° N 78.3° E. It is the second largest glacierized massif in the Tien Shan, covering approximately 400 km^2 (Fig. 1). The first comprehensive glacier inventory of this area was developed by Kuzmichenok [12], using aerial photography, from 1943 and 1977. Along with an estimation of the glacier

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area changes, two DEMs were generated from stereophotogrammetric measurements, with a resolution of 100 m, to estimate glacier volume changes [13]. Recent changes of the Akshiirak glacier area were assessed using an ASTER image acquired on August 19, 2003 [14].

II. Data and Methodology

A. DEMs

We used the "research grade" unedited version of SRTM 3 arcsecond data acquired in the C-band frequency and processed by the National Aeronautics and Space Administration Jet Propulsion Laboratories (NASA JPL). We transformed the SRTM data from WGS 84 to Pulkovo 1942 datum, which is used in the former U.S.S.R., using the Helmert transformation with 2-m accuracy [15]. To avoid resampling, the SRTM grid was converted to vector points and then projected on the Gauss–Kruger topographic map coordinate system.

The DEM for 1977 was generated from 18 sheets of 1 : 25 000-scale topographic maps covering the Akshiirak massif and surrounding area. The nominal vertical accuracy of the maps is one-third of the contour interval (approximately 3.3 m), and the horizontal accuracy is 5 m. On wide homogeneous snow fields, the vertical accuracy is reduced because of the poor contrast of the aerial photographs. This error could not be estimated exactly. We assume that it could reach up to 10 m. The maps were scanned at 300 dpi and georeferenced to the Gauss–Kruger coordinate system using the four corner points for each map sheet. Stability of the paper maps and scanning errors could be estimated by looking at the root-mean-square error (RMSE) of the georeferencing of the scanned maps. The arithmetic average is 2.3 m (minimum 0.74 m and maximum 3.89 m). The 10-m contour lines, elevation spots, and lake boundaries were manually digitized and used for producing a 15-m resolution DEM for 1977, which is generated by the ANUDEM algorithm available in the ArcGIS 9 software package.

B. ICESat Data

We found only one ICESat track crossing the Akshiirak massif (Fig. 1). It was acquired on October 30, 2003, with Laser 2a. We used GLA14 Global Land Surface Altimetry data, release 21. The data were transformed from TOPEX ellipsoid to the WGS84 EGM-96 reference system for comparison with the SRTM data using a set of Interface Description Language (IDL) tools available at the National Snow and Ice Data Center (NSIDC) [16]. Due to the rugged terrain, only 67 laser spots on the flat accumulation and ablation zones of the two largest glaciers were used in our study (parallel to the upper part of profile E and crossing profile C in Fig. 1). We assume that the ICESat data represent the surface at the end of the 2003 ablation season. The amount of precipitation in October and September of 2003 was only 25 mm (3614 m, Tien Shan station).

C. Surface Change Errors

1) DEM Comparison: Numerous studies have shown that the vertical accuracy of the SRTM data exceeds the 16-m requirement (for example, see [17]). However, it is also known that the vertical accuracy of the interferometric synthetic aperture radar (InSAR) DEM degrades over the rugged terrain [18]. To estimate the error of glacier surface change, we compared the SRTM DEM and the DEM 1977 over glacier-free areas (Table I). The DEM differences were calculated for over 110 000 SRTM points on flat depressions surrounding the Akshiirak massif and rock outcrops. There are no forests in the study area that may influence SRTM elevation. Because SRTM-3 data were produced using a three-by-three cell average of the original 1 arcsecond data, the differences were calculated by comparing each SRTM point and the average of the DEM 1977 cells falling inside a 3 × 3 arcsecond window, which is projected on the Gauss–Kruger coordinate system and centered on the point.

TABLE I
Statistics of SRTM DEM Minus DEM 1977 Differences Over Glacier-Free Areas. We Take This as a Measure of Surface Change Error

Slope (degree)	Mean (m)	St. dev. (m)	Min (m)	Max (m)	Count
0-5	0.1	4.4	-38.9	20.3	22412
5-10	-1.8	5.1	-46.1	32.4	20477
10-15	-2.8	6.1	-73.8	36.3	16723
15-20	-3.3	7.3	-51.4	32.4	13012
20-25	-4	8.8	-49.2	33.8	10269
25-30	-4.5	10.9	-307	71.1	9575
30-35	-5.4	12.4	-69.7	65.5	10606
35-40	-6.1	15.1	-267.5	75.2	8578
40-78	-7.6	25.6	-313.3	110.7	5540
all	-3.1	10.1	-313.3	110.7	117192

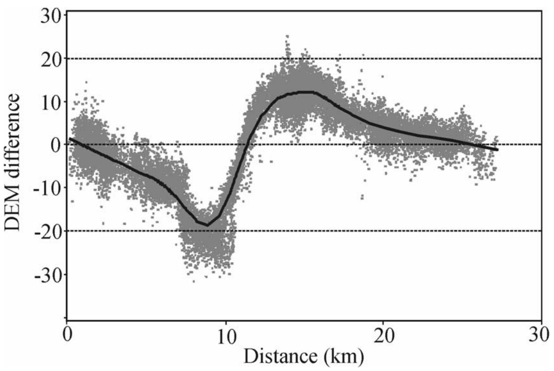

Fig. 2. AB profile (see Fig. 1) of the DEM differences of the SRTM points located to the west of the line. The "wave" has been approximated by a locally weighted polynomial regression (only points on slopes of less then 10° displayed).

Visual analysis revealed systematic error in the western periphery of the study area (separated by line AB in Fig. 1) with a gradient in the DEM differences oriented in the north-western direction. The large amplitude (from −20 to 12 m) of the DEM differences in the direction of line AB (Fig. 2) and the sinusoidal shape of the gradient and its approximate parallelism to the descending shuttle orbit suggest that the systematic error is related to the SRTM data. Rabus *et al.* [6] describe different error sources in the SRTM data, and among them are: 1) the incompletely compensated shuttle antenna mast oscillations (±2.5 m) and 2) the firing of the shuttle attitude control thrusters (±10 m). These two types of errors on a spatial scale of 50–700 km are not reducible by the ocean calibration and filtering done by NASA JPL and may be corrected by users on local areas. Because we did not find any significant trends in the DEM differences in the remaining area to the east of line AB and each SRTM $1^\circ \times 1^\circ$ data tile has combined data of several shuttle "data takes," no corrections were applied to the SRTM data on the glaciers. We excluded from the accuracy analysis the area with the "wave" systematic error to the west from line AB, as well as the areas disturbed by the Kumtor Mining Company, which are determined from the ASTER image.

The standard deviation of the DEM differences is 10.1 m, which is equal to 16.2 m at the 90% confidence level. This estimation combines the 6-m (90%) SRTM relative vertical error, 3.3-m topographic map vertical error, and error due to the slope-related degradation of the SRTM accuracy over the alpine terrain in the study area. Extreme DEM differences from -313 to 110 m are related to very steep rock walls and often located near the SRTM void areas. Table I shows that both random and systematic errors are slope related. If we include in the analysis only the DEM differences on slopes of less than 25°, the standard deviation is 6.3 m.

The mean of the DEM differences of 0.1 m on flat areas confirms the absence of the significant differences between the vertical reference systems of the maps and the SRTM data. However, corrections for systematic errors from -1.8 to -4 m on 5–25° slopes were applied for glacier surface change calculations.

2) Radar Penetration and Seasonal Differences: To calculate the surface elevation changes, we must consider the penetration depth of InSAR signal in snow and ice and winter snow accumulation in the SRTM DEM. Radar penetration at the C-band frequency in dry snow may reach up to 9 m, whereas in exposed ice, it may reach 1–2 m only, as has been shown for Greenland [19].

Winter snow accumulation from September 1999 to February 2000 was only 88 mm (3614 m, Tien Shan station), and negative winter altitudinal gradient of precipitation makes it negligible (less than 1 m at the elevation of the firn line) [20]. Consequently, the following corrections have been added to the DEM differences for radar penetration and winter snow accumulation: 1 m for the clear ice areas (below 4235 m) and a linear increase to 9 m at 4500 m. The elevation of 4235 m was estimated from the SRTM DEM and 2003 ASTER image.

3) Errors on Steep Slopes: The 1943–1977 data [13] show that typical glacier surface changes on steep slopes are less than ±10 m with generally gradual decrease to ridge tops. Because of large random errors of the DEM differences on steep slopes, we used triangular irregular network (TIN) interpolation for estimating surface changes on steep slopes. The TIN was constructed with the DEM differences of the SRTM points of less than 25° (76% as estimated from DEM 1977) and the boundaries of the glacier polygons as zero change. Then, the DEM differences of the SRTM points on slopes of more than 25° and missing points in SRTM void areas were interpolated from the TIN. This approach was tested in a detailed simulation study of two glaciers using surface change data from 1943 to 1977. The simulated surface changes on steep slopes using the TIN interpolation were compared to those directly estimated from the map [10], and a systematic error of 0.6 m was observed. However, the simulated error does not include possible additional errors of surface changes on nonsteep areas involved in the TIN generation.

4) Error Summary: The estimated errors of surface change are spatially variable and mainly depend on slope and elevation. The area-average surface change RMSE of 8.2 m was calculated by weighting the input of different error sources by the slope and elevation distribution of the glacier surface and assuming their independence: 4.4–8.8 m for areas less than 25°, 8.8 m on slopes of more than 25°, and 10.6–12.9 m for areas above 4400 m (36% of total area), where featureless snow cover is dominant and a conservative estimate of the 10-m map error is assumed. This estimate is subject to the error of several meters due to a possible variation of the radar penetration. However, the comparison of the ICESat and SRTM data, as described later, shows an absence of significant systematic errors.

III. RESULTS

The area-average surface change (SRTM minus DEM 1977) of the Akshiirak glaciers is -15.1 m. The total volume change of -6.15 km^3 was calculated by multiplying the average surface change by the area of geometrical union of the 1977 and 2003 glacier polygons. The standard error of volume change of 0.015 km^3 was calculated by dividing the product of surface change error and glacier area by the square root of the number of measurements (SRTM points).

The rate of the Akshiirak glacier volume loss has increased by 2.7 times: from 0.105 $\mathrm{km}^3 \cdot \mathrm{a}^{-1}$ during the period from 1943 to 1977 to 0.279 $\mathrm{km}^3 \cdot \mathrm{a}^{-1}$ during the period from 1977 to 1999. More detailed analysis of the Akshiirak glacier change and climatic causes will be presented in [14].

Several profiles of surface change along the glacier centerlines are presented in Fig. 3. The thinning of the glaciers (up to -126 m) primarily occurred on the large glacier tongues reaching the lower elevations. The estimated average surface change below 4400 m (mainly ablation area) is -19 m (RMSE = 6.3 m), and the standard deviation is 17.5 m. The estimated average surface change above 4400 m is -7.5 m (RMSE = 10.9 m), and the standard deviation is 12.9 m. In spite of a low signal-to-noise ratio above 4400, the results are informative. Local areas of thinning/thickening (up to ±40 m) are present on the flat upper accumulation areas, and most of them are closely related to similar areas in the 1943–1977 data [13], with opposite surface change (for example, see Fig. 4, eastern corner of the glacier).

Six of the glaciers show surging behavior with up to ±60-m surface changes involving full width of a glacier or a particular branch. In Fig. 4, a glacier with a surging northern branch is shown. The 1943–1977 data show more than 20 m of thickening on the area dammed by the central glacier flow, which was followed by up to 48 m of thinning in the second period (Fig. 5).

The difference of SRTM minus ICESat elevations of 67 laser spots has been found to be approximately linearly related to elevation (Fig. 6). This could be explained by: 1) the ablation during summer of 2000–2003, which mainly depends on the altitudinal temperature gradient and 2) the radar penetration in the SRTM data. If we apply the same correction for radar

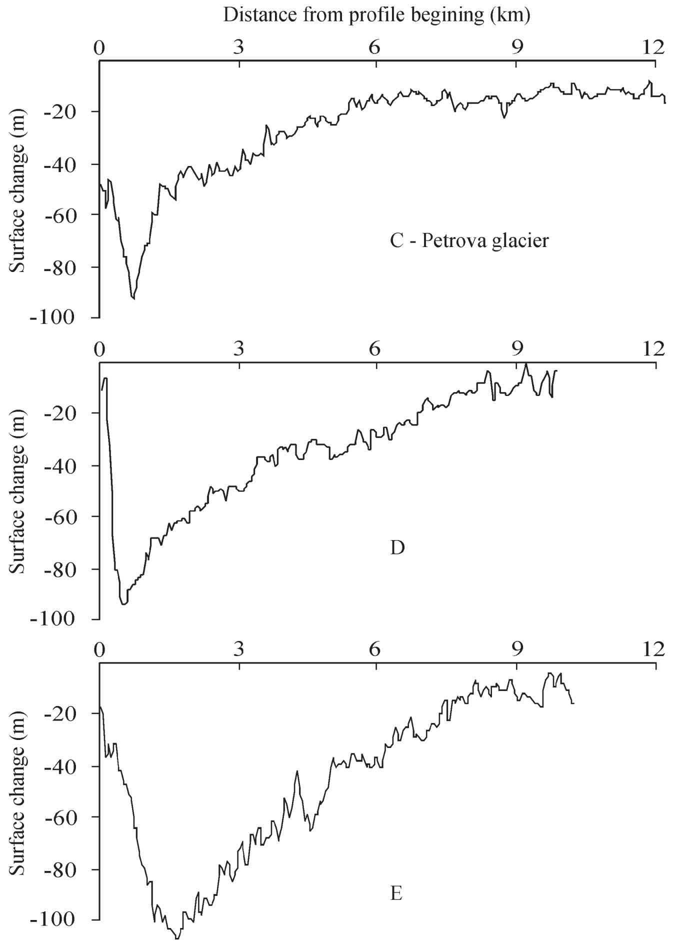

Fig. 3. Surface change profiles (see Fig. 1) of the three largest Akshiirak glaciers. The 6–8-m fluctuations of surface change represent random error of measurements.

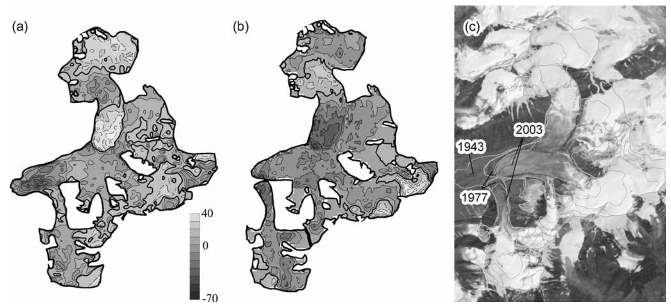

Fig. 4. Glacier in the Akshiirak massif showing surging behavior. (a) Surface change 1943–1977 (in meters). (b) Surface change 1977–1999 (in meters) (contour lines: thick solid, zero change; thin solid, negative change; dashed, positive change). (c) Area in 1943, 1977, and 2003 on the 2003 ASTER image and 100-m contour lines.

penetration as previously mentioned, then the average of SRTM minus ICESat differences above 4235 m is 0.08 m, with a standard deviation of 4.3 m, which could be expected on a relatively stable accumulation area during a short period. The mean difference on the Petrova glacier tongue (12 laser spots) is -9.4 m, and the standard deviation is 2.5 m. The rate of ablation surface thinning of $2.1\ \mathrm{m \cdot a^{-1}} \pm 0.2\ \mathrm{m \cdot a^{-1}}$ during the period from 1977 to 1999 has not significantly changed to the estimated rate of $2.4\ \mathrm{m \cdot a^{-1}} \pm 0.8\ \mathrm{m \cdot a^{-1}}$ during the period from 1999 to 2003.

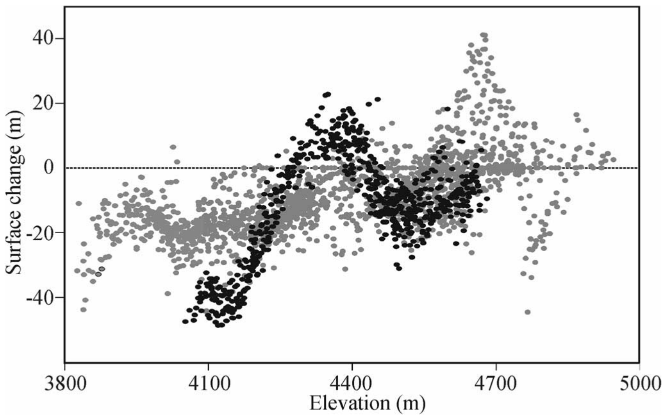

Fig. 5. Surface changes from 1977 to 1999 of the surging glacier shown in Fig. 4. Black dots represent surface changes of a northern glacier branch. Gray dots represent surface change of the remaining area. The ±40-m surface changes above 4600 m are closely related to the opposite changes in the 1943–1977 data.

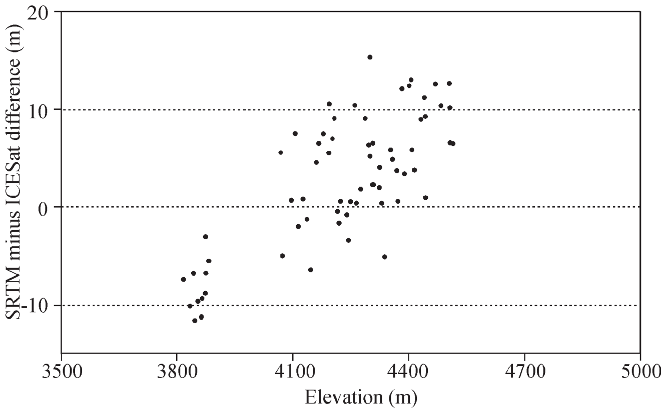

Fig. 6. Difference between the SRTM DEM and ICESat elevations of 67 laser spots on the flat ablation and accumulation areas of Akshiirak glaciers.

IV. DISCUSSION

The method of glacier thickness and volume change estimation using the SRTM and map-based topographic data was successful.

To ensure the most possible accuracy, SRTM DEM should be checked on flat areas for local systematic errors if a study area stretches for more than 50 km. To the best of our knowledge, the "wave" found in the SRTM data in our study has not been previously reported. Further elimination of and/or compensation for the errors is possible if the coverage of the particular "data takes" and accuracy estimates are known (currently available only for commercially distributed SRTM-X data).

SRTM data on flat areas located close to steep valley walls and high peaks should be carefully considered because shadows and layover may degrade the InSAR signal, not only on steep slopes, but also on the adjacent flat areas [18]. For example, several SRTM points show an unrealistically high thickening of 78 m at the base of a southern slope of a glacier-covered peak (4806 m) while suggesting a thinning of -98 m at the same elevation at the base of a southeastern slope. However, we cannot exclude the possibility of a snowmass accumulated from avalanches.

Our results significantly differ from those published in [21]. From the ratio of thinning to area change observed for the

1943–1977 period, the reported 23% area reduction reported in [15] would seem to imply thinning of 45 m in the 1977–2001 period. Assuming the same ratio of thinning to area change and our estimate of 8.6% of area reduction from 1977 to 2003 [11], the average surface thinning from 1977 to 1999 would be 13.8 m, which is close to our estimate of 15.1 m.

V. CONCLUSION

This paper shows the applicability of the SRTM data for assessing mountain glacier thickness and volume changes. In spite of the SRTM error and the occasional absence of data on steep slopes due to layover and shadow, major long-term changes on relatively flat ablation and accumulation areas are clearly identifiable. The presence of local areas of rebound allows us to distinguish dynamic and climatic components of glacier changes that are not available solely from planimetric data. The free access to SRTM-3 data can facilitate very cost-effective regional assessments of glacier thickness/volume changes of major glaciated areas in midlatitude and low latitude if previous topographic data exist. Comparison of SRTM and ICESat data also allows estimation of short-term surface changes of mountain glaciers.

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