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Change in the glacier extent in Turkey during the Landsat Era

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ABSTRACT

We report the latest study for small glaciers, using Turkey as an example, and update previous studies of glaciers in Turkey from the 1970s to 2012–2013. We used seventy-two Landsat scenes from the Multispectral Scanner (MSS), Return Beam Vidicon-3 (RBV-3), Thematic Mapper (TM), Enhanced Thematic Mapper plus (ETM+), and Operational Land Imager (OLI); five Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images; and forty-one commercial satellite images. IKONOS, Quickbird-2, GeoEye-1, and WorldView-1 and -2 commercial satellite images were used to evaluate mapping accuracies, to understand debris-covered glacial margins, to map glacier margins in shadows, and to better determine the area of the smaller glaciers in Turkey. We also used nine Landsat-5 simultaneously acquired TM and MSS images to more accurately process MSS imagery from the 1970s. The area of the glaciers in Turkey decreased from 25 km^2 in the 1970s to 10.85 km^2 in 2012–2013. By 2012–2013, five glaciers had disappeared, six were less than 0.5 km^2, one was 0.8 km^2, and only two were 3.0 km^2 or larger. No trends in 1980 to 2012 annual precipitation, 1980 to 2012 winter precipitation, and 1980 to 2008 cloud cover extent were found, while surface temperatures increased, with summer minimum temperatures showing the greatest increases. We attribute glacier recession in Turkey from the 1970s to 2012–2013 to increasing summer minimum temperatures with no changes in precipitation or cloud cover over this time period.

1. Introduction

Turkey is located between 36° N and 42°N latitudes, 26° E, and 45° E longitudes. It is a mountainous country, with an average elevation of 1,132 m above sea level. Approximately half of the country is comprised of mountains and hills, with the highest elevations located in the eastern part. Annual snowfall in winter exceeds 2 m in the higher mountain ranges (Kurter, 1988). Climate is effected by continentality, and this effect increases with distance from the coast to the interiors. Glaciers exist in Turkey on three stratovolcanoes and on high peaks in the Southeastern Taurus Mountains; the Middle Taurus Mountains, including an extension of this range called the Mercan (or Munzur) Mountains into the interior of Turkey; and in the Eastern Black Sea Mountains. The mountain peaks that host glaciers in the 1970s were reported by Kurter (1988) to be Mt. Kaçkar, Mt. Verçenik, Mt. Aptalmusa, and Mt. Karagöl in the Eastern Black Sea Mountain region; Mt. Medetsiz and Mt. Demirkazık in the Middle Taurus Mountains; Mt. Buzul, Mt. Hasanbeşir, and Mt. Dolampar in the Southeastern Taurus Mountains; and Mt. Ağrı, Mt. Süphan, and Mt. Erciyes on dormant stratovolcanoes. The summary by Kurter (1988) has been augmented by Sarıkaya, Çiner, and Zreda (2011) and Çiner (2004), who describe a few glaciers not described by Kurter (1988), including Kırmızıgedik and Avucur in the Eastern Black Sea Mountains and Gedik and adjacent glaciers in the Mercan Mountains in the central northeast of Turkey. We have combined these three sources to comprise the fourteen glaciers of Turkey that we have studied (Fig. 1 and Table 1).

There are limited historical descriptions of glaciers in Turkey before the 1930s. Ainsworth (1842) noted the presence of glaciers in the Southeastern Taurus Mountains, and Palgrave (1872) noted glaciers in the Eastern Black Sea Mountains. Observations of selected glaciers in Turkey were reported by Maunsell (1901), but there were no systematic attempts to study individual glaciers until the 1930s. These pre-1930s accounts provide little useful information on the extent or margins of any glaciers in Turkey.

Starting with Leutelt (1935) and Bobek (1940), scientific study of Turkey's glaciers began and continued with the post World War II efforts by Turkish geographers, especially Erinç (1953, 1971) and Atalay (1987), and foreign scientists Birman (1968) and van Arkel (1973). Satellite studies of glaciers in Turkey include the early work of Kurter and Sungur (1980) and Kurter (1988) and more recent studies by Çiner (2004) and Sarıkaya et al. (2011), a detailed study of the Mt. Ağrı ice cap by Sarıkaya (2012), and a recent inventory of glaciers in Turkey by Sarıkaya and Tekeli (2014). We update the studies by Sarıkaya (2012) and Sarıkaya and Tekeli (2014) by using time-series

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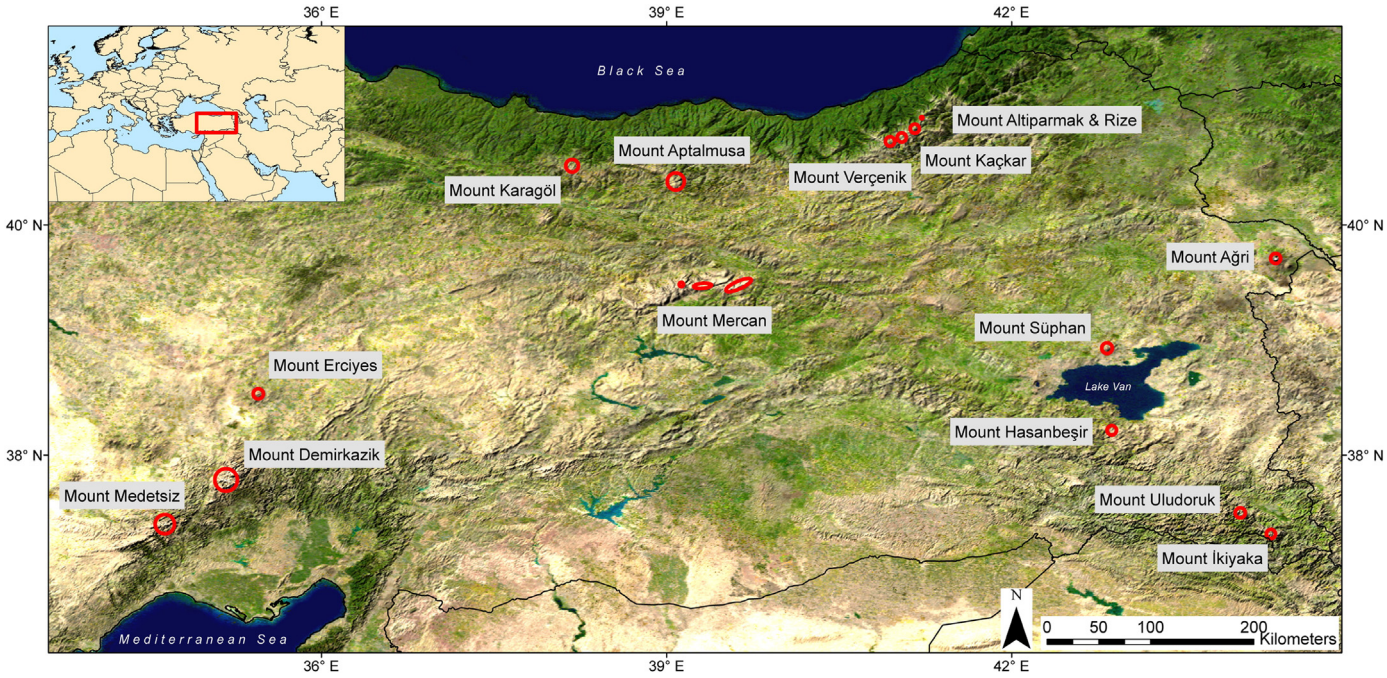

Fig. 1. The location of glaciers in Turkey is concentrated in four areas: (1) the south central Turkey (north of the Mediterranean coast); (2) the northeast Turkey (south of the Black Sea); (3) the central northeast of Turkey (further south of the Black Sea); and (4) the far east and southeast, adjacent to Iran and Iraq. We used Kurter (1988), Çiner (2004), and Sarıkaya et al. (2011) to identify the glaciers in this figure. See also Table 1.

Landsat and ASTER instrument analyses complimented by more recent commercial satellite data.

Before 1945, and the subsequent acquisition of vertical aerial photography, there was little information about Turkey's glaciers that could be used quantitatively, and no inventory of any glaciers exist by a systematic methodology. While post-1945 vertical aerial photography exists, it is difficult to use for Turkey's glacier mapping because this was not the objective of these acquisitions. Because of the high elevations of glaciers, there is frequently confusion between glacier and snowfall, even in summer, and clouds. This is exacerbated by the black-and-white panchromatic aerial photography acquired.

With the launch of Landsat's 1, 2, and 3 beginning in 1972, MSS imagery was collected from all the areas where glaciers exist in Turkey. However, MSS data suffer from several limitations: a spatial resolution of 60 m for MSS images, radiometric resolution of 64 quantizing levels, no ice-cloud discriminating shortwave infrared spectral band, and limited repeat acquisitions. Improvements were made to the RBV instrument on Landsat-3 that made this instrument superior to the MSS for glacier mapping. The RBV-3 imaged an entire ground scene instantaneously and provided greater cartographic fidelity than the MSS. The RBV-3 on Landsat-3 had 40-m pixel resolution and is a better data source than the MSS for glacier studies where these data exist. A major limitation of the RBV-3 instrument, like the MSS, is the lack of a shortwave infrared band for separating cloud from snow and ice.

Limitations of the MSS and RBV-3 instruments for glacier studies were corrected with the launch of Landsat-4 in 1982 and Landsat-5 in 1984 with their TM instruments, by Landsat-7's ETM+ instrument launched in 1999, by the launch of the ASTER instrument on the Terra EOS platform in 2000, and by the launch of Landsat-8 with its OLI instrument in 2013. Not only has there been more frequent acquisition of satellite data since the mid-1980s, but Landsat's TM/ETM/ETM+/OLI and ASTER's spectral bands and 30 m spatial resolution and the ETM+'s and OLI's 15-m panchromatic band enabled quantitative mapping of all the glaciers of Turkey. Improved quantitative study of Turkey's glaciers was thus possible for the first time starting in 1982, although an aggressive satellite acquisition strategy did not exist until 1999 with the launch of Landsat-7 and an open Landsat data policy that started in 2005. Since 2005, quantitative and systematic studies of

Table 1
The principal glaciers of Turkey, their mountain ranges and elevation, the coordinates of each mountain, and the glacier names.

Mountain (s)	Peak elevation (m)	Location	Glacier name (s)
Mount Ağrı	5,137	39°41′–39°44′N 44°15′–44°19′E	Ağrı
Mount Uludoruk	4,135	37°26′–37°32′N 43°56′–44°04′E	Uludoruk
Mount Süphan	4,058	38°53′–38°57′N 42°47′–42°52′E	Süphan
Mount Kaçkar	3,932	40°49′–40°51′N 41°08′–41°11′E	Kaçkar
Mount Erciyes	3,917	38°31′–38°34′N 35°24′–35°28′E	Erciyes
Mount İkiyaka	3,794	37°18′–37°24′N 44°10′–44°20′E	Geverok
Mount Demirkazık	3,756	37°41′–37°55′N 35°02′–35°16′E	Lolut
Mount Verçenik	3,710	40°40′–40°47′N 40°52′–41°05′E	Sinançor
Mount Altıparmak and Rize	3,562	40°30′–40°32′N 38°08′–38°13′E	Kırmızıgedik & Avucur
Mount Medetsiz	3,524	37°21′–37°26′N 34°30′–34°41′E	Medetsiz
Mount Hasanbeşir	3,503	38°12′–38°14′N 42°48′–42°58′E	Hasanbeşir
Mount Mercan	3,368	39°22′–39°36′N 39°00′–39°60′E	Gedik
Mount Aptalmusa	3,331	40°22′–40°26′N 39°02′–39°07′E	Avliyana
Mount Karagöl	3,107	40°30′–40°32′N 38°08′–38°13′E	Karagöl

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