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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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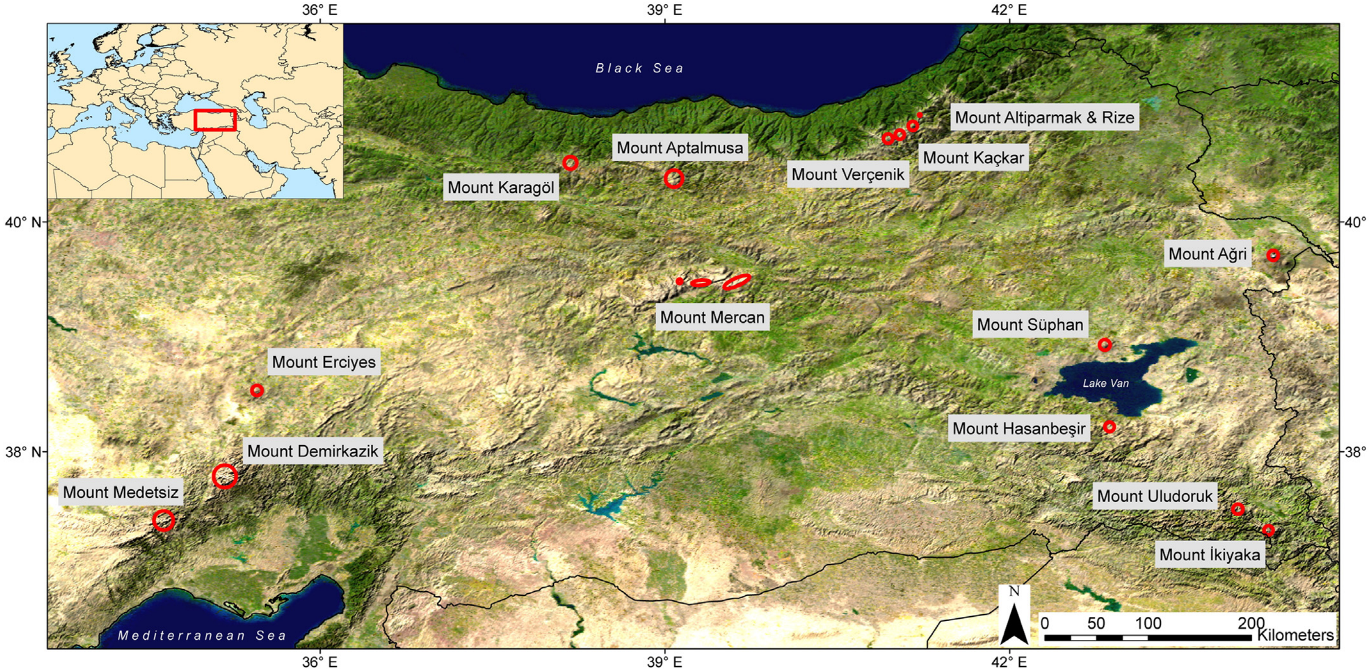

Fig. 1. The location of glaciers in Turkey is concentrated in four areas: (1) the south central Turkey (north of the Mediterranean coast); (2) the northeast Turkey (south of the Black Sea); (3) the central northeast of Turkey (further south of the Black Sea); and (4) the far east and southeast, adjacent 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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Turkey's glaciers have proceeded and we report new results using a large quantity of Landsat-1, -2, -3, -4, -5, -7, and -8; ASTER; and commercial satellite data.

Our basis for studying glacier extent in Turkey since the 1970s is Kurter (1988), who used 1:500,000 prints of Landsat MSS 60-m data and Landsat-3 RBV 40-m imagery interpreted photographically, plus the work of Çiner (2004) and Sarıkaya et al. (2011), who used Landsat as well as ASTER data. We started from the work of Kurter (1988), as described in Williams and Ferrigno (1998), Çiner (2004), and Sarıkaya et al. (2011) and studied in detail the fourteen glaciers identified by these sources. By using the powerful combination of many MSS, TM, ETM+, ASTER, and OLI images, in combination with selected ≤1 m spatial resolution commercial satellite images from the past decade, we were able to quantitatively document the areal extent change of all Turkey's glaciers for the first time. We also used the high accuracy of the TM mapping capability to guide our analyses of Landsat-1, -2, and -3 MSS images, including analysis of eight pairs of simultaneously collected Landsat-5 MSS and TM imagery for eight of Turkey's glaciers. Knowing where glacier ice existed in the 1980s with both the TM and the MSS instruments enabled us to better process the 1970s MSS data.

2. Data and methods

Remote sensing of glacier extent involves the analyses of multi-temporal satellite data over the glacier areas in question. We used Landsat data from 1972 to 1980 from the Landsat MSS and the Landsat-3 RBV instruments; from the TM, ETM+, and OLI instruments from 1982 to 2013; and commercial satellite imagery from 2003 to 2013 from IKONOS, Quickbird-2, GeoEye-1, WorldView-1, and WorldView-2 satellites for our study of glacier extent in Turkey. The IKONOS, Quickbird-2, GeoEye-1, WorldView-1, and WorldView-2 imagery (≤1 m spatial resolution and high radiometric resolution) were extremely useful in mapping several very small glaciers or their fragments, confirming glacial margins detected in TM imagery, and identifying debris-covered glacier margins. The high level of radiometric resolution of the commercial satellite also data also enabled the mapping of glacier margins in shadows, a major improvement in glacier studies.

When using multi-temporal satellite data, it is critical to ensure all data used are orthorectified and co-registered to all other images from the same area. This is needed to prevent registration error, where these errors are confused with glacier recession or expansion. To achieve a very high degree of among-image registration, we obtained the one arc second ASTER digital elevation data and used this as the basis for registration of all satellite images. We estimate our orthorectification error to be less than ±30 m.

It has long been noted that glacier mapping confusion results when snow is present in conjunction with glacier ice. To minimize this source of error, we used multiple summer images where possible for every glacier studied and selected the minimum snow-cover area per time period (Table 2).

Because of the spectral and spatial differences of the data set, we used a combination of glacier mapping approaches. We formed false-color composites using SWIR, NIR, and red bands and employed the normalized difference snow index (Hall, Riggs, & Salomonson, 1995), TM4/TM5 band ratio for TM, ETM+ OLI, and ASTER data to identify snow, ice, and other scene constituents. We manually delineated glacier boundaries using visual interpretation. The commercial satellite scenes were panchromatically sharpened for multispectral data or used as panchromatic data for WorldView-1. These data were superimposed over our delineated Landsat or ASTER images and used to refine mapping of glacier and non-glacier margins. Even when glacier margins were covered in debris, we were able to discern ice beneath it by the structure of the glacier expressed through the debris. All the digitization has been done in ESRI ArcGIS 10.2 software.

We investigated eleven smaller glaciers reported in Kurter (1988), Çiner (2004), and Sarıkaya et al. (2011), all of which thought to be smaller than 1.0 km^2 in area in the 1970s (Table 2). We acquired Landsat-4 and Landsat-5 TM data, Landsat-7 ETM+ data, Landsat-8 OLI data, ASTER data, and commercial satellite data for these glaciers, in addition to acquiring Landsat MSS and Landsat-3 RBV-3 imagery. To guide our analyses of MSS data, we analyzed eight simultaneously acquired MSS and TM scenes from Landsat-5. We analyzed a total of 14 Landsat images for the 1970s, 22 images for the 1980s, 14 images for the 1990s, 13 images for the 2000s, and 9 images for the 2010s, in addition to 5 ASTER and 41 commercial satellite images.

While there is a clear ice/non-ice difference in spectral reflectance, complications arise when glacier margins are covered by debris. This makes glacier/non-glacier delineation difficult and sometimes impossible. To minimize this problem for data from 2003 to 2013, we analyzed high spatial resolution commercial satellite data imagery for thirteen of fourteen glaciers in Turkey. These data were very useful for identifying debris-covered glacial areas, determining glacial margins in shadows, refining our margin mapping and thus minimizing area error. For determinations of areal extent of glacier ice extent in the 1970s, 1980s, 1990s, and 2000s, we mapped the glacier/non-glacier boundaries, as they were evident in the satellite data for all time periods. We acknowledge minor errors in

Table 2
Summary of the glaciers of Turkey, complied from Kurter (1988), Çiner (2004), and Sarıkaya et al. (2011). We include glacier names and elevations. Kurter (1988) refers to the reported areas circa 1970 from this source plus those of Çiner (2004) and Sarıkaya et al. (2011). Our results are reported for the 1970s using MSS and RBV-3 data. Our results using Landsat-4, -5, -7, and -8 data are reported for the mid-1980s, mid-1990s, 2007–2011, and 2012–2013. ASTER imagery were used for Mt. Ağrı for 2007–2011 and for 2012–2013. We also used 41 commercial satellite images from 2003 to 2013 from thirteen of fourteen glaciers of Turkey (see Table 3).

Glacier	Peak elevation (m)	Kurter, 1988 (km^2)	1970s (km^2)	1980s (km^2)	1990s (km^2)	2007–2011 (km^2)	2012–2013 (km^2)	Year of last data
Ağrı	5,137	10.0	8.9	8.7	7.1	5.60	5.34	2013
Uludoruk	4,135	8.0	8.5	5.5	4.1	3.90	3.51	2011/2012
Süphan	4,058	3.0	1.3	1.0	0.8	0.34	0.31	2012
Kaçkar	3,932	0.1	1.8	1.8	1.3	0.25	0.25	2011
Erciyes	3,917	0.1	0.5	0.5	0.1	0.00	0.00	2010
Geverok	3,794	0.8	1.5	1.4	1.1	1.03	0.83	2012
Lolut	3,756	0.5	0.0	0.0	0.0	0.00	0.00	2013
Sinançor	3,710	0.1	0.3	0.3	0.1	0.00	0.00	2011
Kırmızıgedik & Avucur	3,562	N/A	0.3	0.3	0.2	0.07	0.02	2013
Medetsiz	3,524	0.1	0.0	0.0	0.0	0.00	0.00	2007
Hasanbeşir	3,503	0.1	0.1	0.1	0.1	0.10	0.10	2011/2012
Gedik	3,368	N/A	1.6	1.4	0.8	0.45	0.45	2013
Avliyana	3,331	0.0	0.1	0.1	0.0	0.00	0.00	2011
Karagöl	3,107	0.1	0.1	0.1	0.1	0.04	0.04	2012
Total (km^2)		22.9	25	21.2	15.8	11.8	10.85	

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our glacier mapping, but use the same methodology for all glaciers for the pre-2011–2013 period.

3. Results

3.1. Mount Ağrı

The ice cap on Mt. Ağrı, also known as Mt. Ararat, is the highest at 5,137 m and largest glacier in Turkey. Located in the eastern part of Turkey adjacent to Iran, Mt. Ağrı is a dormant stratovolcano. Kurter (1988) reported the ice cap there to have a pre-1970 surface area of 10.0 km^2, the same number quoted by Blumenthal (1958). Sarıkaya (2012) has produced a recent study of the Mt. Ağrı glacier area from 1976 to 2011. We independently determined the Mt. Ağrı glacier had a surface area of 8.9 km^2 using MSS data from 1977 while Sarıkaya reported 8.0 ± 0.8 km^2. Our TM data analysis from 1987 and 1989 determined Mt. Ağrı's glacier area to be 8.7 and 8.6 km^2, respectively, as compared to Sarıkaya's (2012) reported 7.0 ± 0.71 km^2 for 1989. TM data from 1998, and ETM+ data from 2000, found glacier areas of 7.1 km^2 and 6.7 km^2, respectively, while Sarıkaya (2012) reported 6.1 ± 0.61 km^2 of glacier extent in 2000. Additional TM and ETM+ data found the Mt. Ağrı glacier area in 2004 had decreased further to 6.3 km^2, decreased in 2006 to 6.0 km^2, further decreased in 2007 to 5.6 km^2, and continued its decrease to 5.3 km^2 in 2012–2013 as measured by ASTER data. IKONOS data from 2003 gave an area estimate of 6.5 km^2, which compares well to our Thematic Mapper 2003 result of 6.3 km^2 and Sarıkaya and Tekeli (2014), who found 6.20 ± 0.62 km^2 of glacier extent in 2002 (Fig. 2). Our area results were similar to the estimates of Sarıkaya's (2012) measurements from the mid-1970s to 2012. We attribute the minor differences between our Mt. Ağrı glacier extent measurements and those of Sarıkaya (2012) from our use of commercial satellite data that refined glacier margin mapping of the Mt. Ağrı glacier where debris or shadow was present and our application of this knowledge to previous years.

There is a strong aspect and elevation component to the 1977 to 2013 glacier loss on Mt. Ağrı, with minimal loss occurring on the northern aspects of the glacier and maximum loss taking place on the southern, western, and eastern glacier aspects, all at lower elevations. In addition, from 1977 to 2013 significant fragmentation occurred at lower glacier elevations, with many glacier areas becoming isolated from the contiguous body of the glacier on the southern and southeastern aspects of Mt. Ağrı (Fig. 2).

3.2. Uludoruk Glacier

In the extreme southeast corner of Turkey lies a portion of the Taurus Mountains that contains both Mt. Uludoruk and also Mt. Dolampar, one of the small glaciers we report on. The Uludoruk Glacier, a valley glacier, was reported to have a 1950s surface area of 8 km^2 with a peak altitude of 4,135 m (Kurter, 1988). The Uludoruk Glacier is

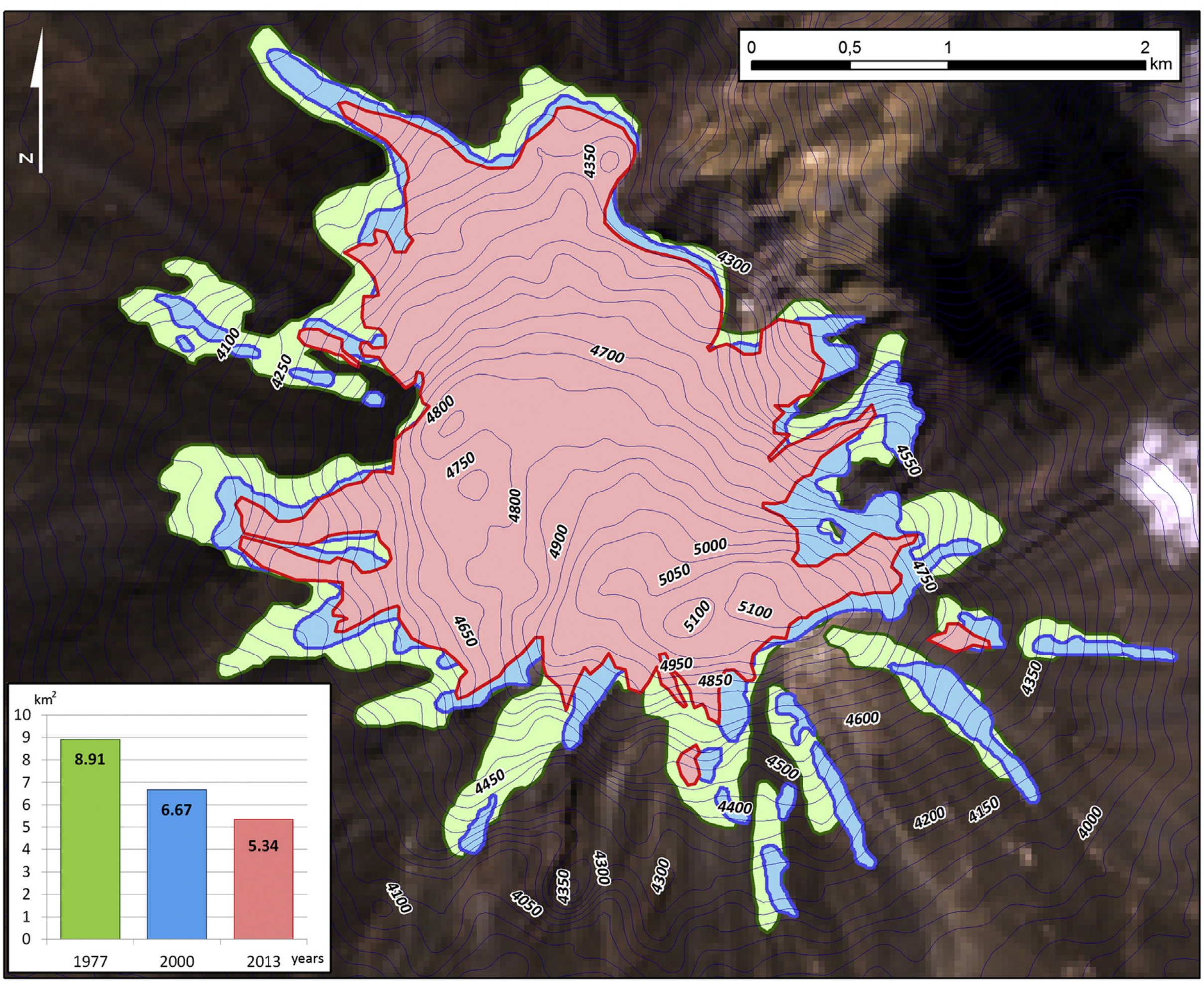

Fig. 2. Multi-temporal glacier change for three dates over 36 years for Mt Ağrı, elevation 5137 m, the largest glacier in Turkey. The background image is a 2000 Landsat TM image using bands three, two, and one as red-green-blue colors with one arc second ASTER digital elevation data incorporated into the image as contours. The majority of the glacier recession from 1977 to 2013 occurred at lower elevations with western, southern, and eastern aspects. MSS data were used for 1977, ETM+ data were used for 2000, and ASTER data were used for 2013. See also Table 2. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

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assumed to have been contiguous in the recent geological past but has been fragmented at least since its first descriptions in the 19th century (Erinç, 1953). The distinct glaciers on Mt. Uludoruk include the Erinç Glacier, on the far western portion of the peak; the West, Middle, and East Mia Havara Glaciers in the Cennet-Cehennem Valley; the İzbırak Glacier in the southeast; and a string of now fragmented glaciers ~ 2 km north of the İzbırak Glacier, than run for ~4 km in a west-north west to east southeast orientation. In addition, there are other glacier fragments around the İzbırak Glacier to the north, south, and east. We refer to all of these glaciers as the Uludoruk glacier (Fig. 3).

Analysis of MSS data from the Uludoruk Glacier in 1977 determined a total area of 8.5 km^2. A generally monotonic decrease in the extent of the Uludoruk Glacier with time was found with 6.0 km^2 mapped in 1984, 5.1 km^2 mapped in 1986, 4.7 km^2 mapped in 1987, 4.5 km^2 mapped in 1990, 4.1 km^2 mapped in 1998, 3.9 km^2 mapped in 1999, 3.9 km^2 mapped in 2007, all from Landsat's TM, and ETM + instrument. A 2010 Worldview-1 image found Uludoruk's area to be 3.51 km^2, less than half of its area in 1970s (Fig. 3).

3.3. Other smaller glaciers

Mt Süphan is another dormant stratovolcano and located north of Lake Van in southeastern Turkey and has a summit elevation of 4,058 m. The crater of Mt Süphan contains several glaciers. We mapped the glaciers on Mt. Süphan in 1977 with MSS data and found 1.3 km^2 of glacier area. Kurter (1988) circa 1970 reported area of 3.0 km^2 for the glaciers on this mountain. Using more detailed TM imagery for 1984, we documented a glacier area of 1.0 km^2 that decreased to 0.93 km^2 in 1987. By 1998, the glacier area had decreased further to 0.8 km^2 and has continued to decrease in extent, falling to 0.7 km^2 in 1999 and 0.5 km^2 in 2000. In 2006 and 2007, we found 0.4 km^2 glacier area for Mt. Süphan (0.38 and 0.35 km^2, respectively), GeoEye-1 imagery found 0.34 km^2 of glacial extent in 2011, and a Landsat-8 2012 image found 0.31 km^2 of glacial ice (Fig. 4).

While Figs. 2, 3, and 4 present multi-temporal Landsat and ASTER images for the two largest glaciers and Süphan, a smaller glacier, Fig. 5 shows the mapping details apparent with a 2003 Quickbird-2 60 cm spatial resolution commercial satellite image of Mount Ağrı. This image shows the utility of using these data to map glacier margins and determine where glacier margins are covered by debris. We used forty-one commercial satellite images to refine our ice/non-ice mapping of several glacier margins that were covered in debris, soil, or shadow. We also used eight Landsat-5 same-day MSS and TM images from 1985 and 1986 to improve our 1970s mapping with MSS and/or RBV-3 data alone. We attribute our differences from other sources in the 1970s extent of Mt. Ağrı's, Uludoruk's, and Mt. Süphan's glacier extent to our combined use of same-day MSS and TM imagery in 1985 and 1986 that enabled better use of MSS or RBV-3 imagery from the 1970s. We attribute our differences from other sources in our 2005 to 2013 glacier extent mapping to our extensive use of commercial satellite data that enabled improvements in mapping glacier margins and also enabled mapping glacier margins in shadow due to the higher radiometric resolution of commercial satellite data (Table 2).

Another smaller glacier, Kaçkar Glacier, is located at an elevation of 3,932 m in the Eastern Black Sea Mountains and was reported by Kurter (1988) to have an area of 0.1 km^2. Thematic Mapper analyses found 1.8 km^2 of glacier in 1987, decreasing to 1.3 km^2 in the mid-1990s. Our analyses of Kaçkar glacier in 2011 with WorldView-2 imagery found 0.25 km^2 glacier area. The MSS data from the 1970s were difficult to use and we used our 1987 TM value for the 1970s glacier extent. Kurter's (1988) value of 0.1 km^2 was in error because much of the Kaçkar glacier is covered by debris. This was easy to discern in the 2011 WorldView-2 image and this image was used to guide our analysis

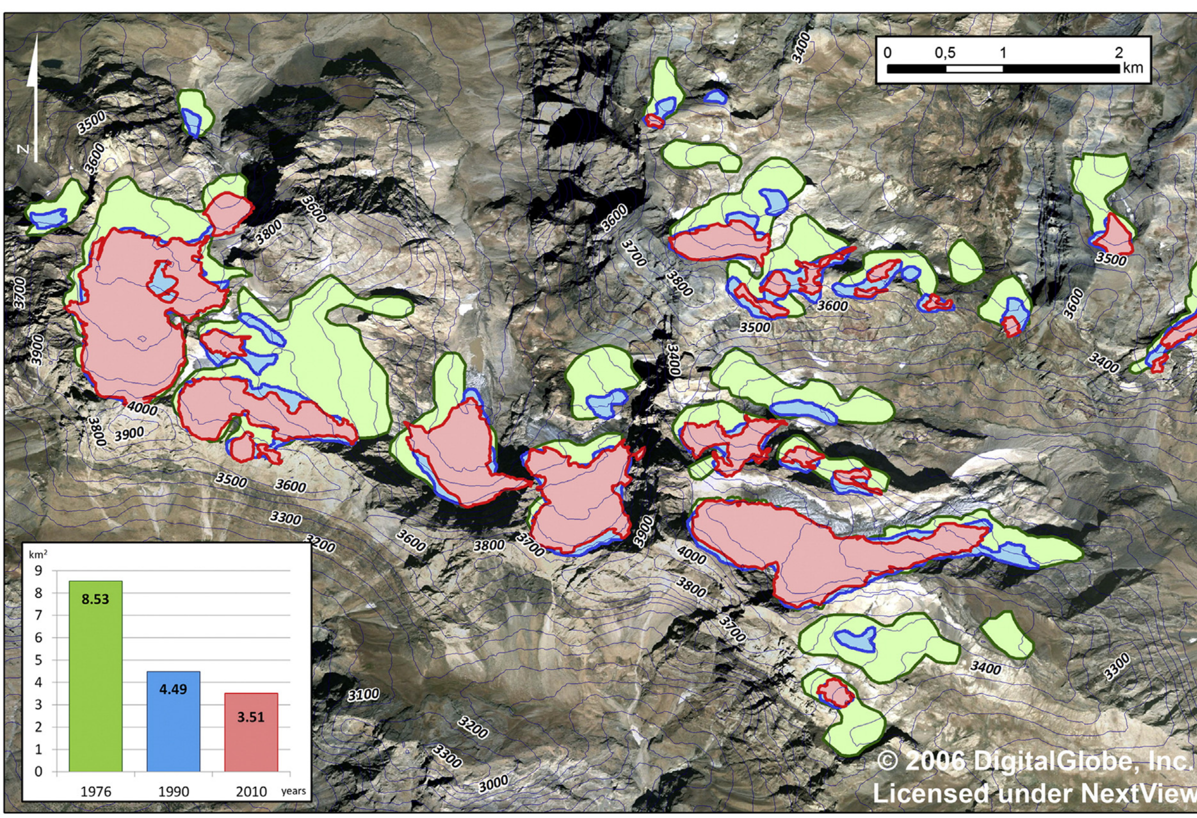

Fig. 3. Glacier change for three dates over 34 years for Uludoruk, elevation 4135 m, the second largest glacier in Turkey. The background image is a year 2006 Quickbird-2 image using bands three, two, and one as red, green, and blue colors with one arc second ASTER digital elevation data incorporated into the image as contours. MSS data were used for 1976, TM data for 1990, and WorldView-1 data for 2010. See also Table 2. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

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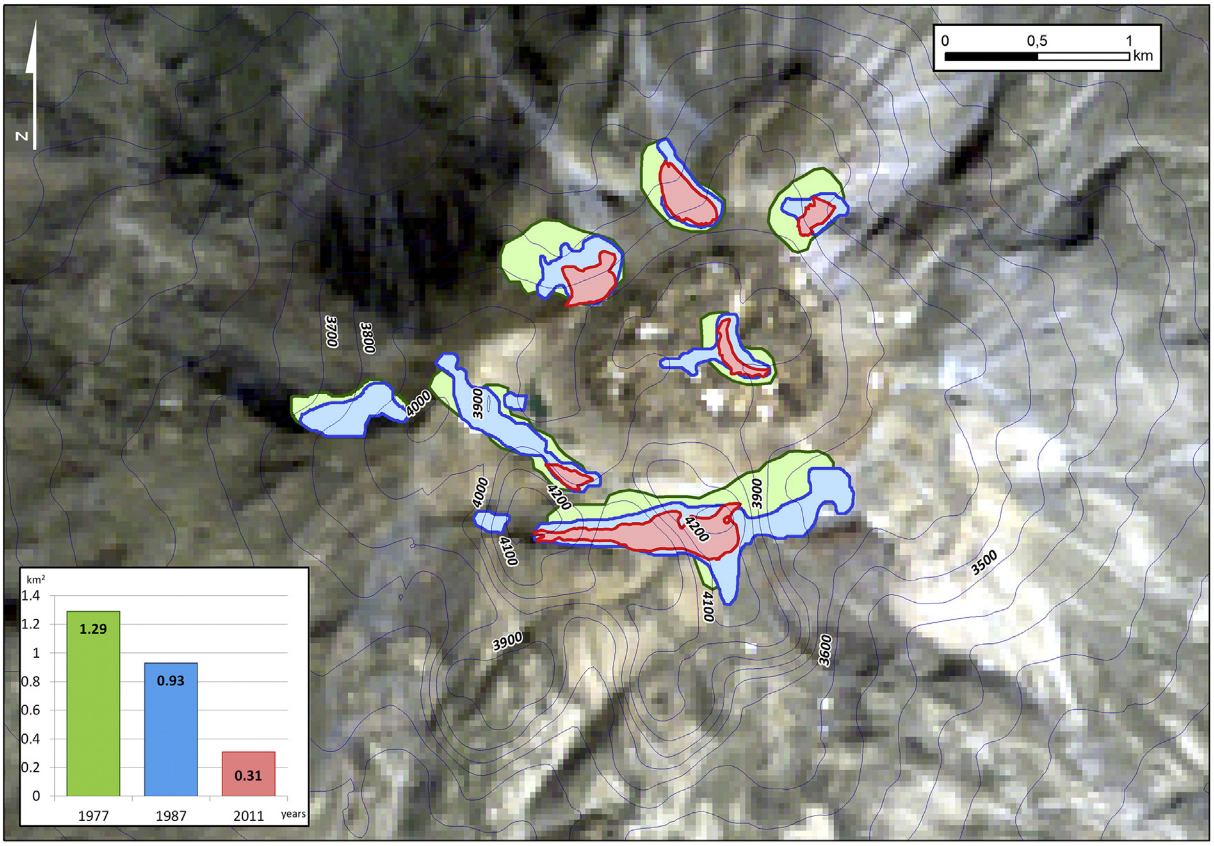

Fig. 4. Glacier change for three dates over 34 years for Mt Süphan, elevation 4058 m, the third largest glacier in Turkey. The background image is a 2007 Landsat ETM+ image using bands three, two, and one as red-green-blue colors with one arc second ASTER digital elevation data incorporated into the image as contours. MSS data were used for 1977, TM data were used for 1987, and GeoEye-1 data were used for 2011. See also Table 2. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

of TM and ETM+ imagery. Field verification in 2012 by two of the authors confirmed this.

Erciyes Glacier is located at 3,917 m elevation on a stratovolcano close to the town of Kayseri. Kurter (1988) reported this glacier to have an area of 0.06 km^2 in the 1970s. Our 1980s TM analysis found 0.5 km^2, which we also used for our 1970s value because the remaining glacier was fragmented into several smaller pieces. This glacier was further reduced to 0.1 km^2 in the mid-1990s in our TM imagery and a WorldView-2 image from 2010 found only 0.002 km^2 remained, and that in several pieces. This also was confirmed by field verification in 2012.

Geverok Glacier on Mount İkiyaka or Mount Dolampar is located at 3,794 m in the Southeastern Taurus Mountains in the extreme southeast of Turkey close to the Iraq border. Kurter (1988) reported this glacier to have an area of 0.8 km^2 in the 1970s and we found an area of 1.5 km^2 in 1974. Geverok's area decreased to 1.4 km^2 in 1985, and further decreased to 1.1 km^2 in 1994. Commercial satellite images between the years 2008 and 2010 of Geverok Glacier found 1.03 km^2 of glacier remaining and a 2012 Landsat-7 ETM+ images found 0.83 km^2.

Lolut Glacier is located at 3,756 m elevation on Mount Demirkazık. While Kurter (1988) reported 0.5 km^2 of glacier area in the 1970s, we found no glacier ice present in TM images from 8 October 1987, 22 October 1998, and 12 August 2007. GeoEye-1 imagery from 2010 indicated no ice was present and we conclude this glacier had vanished by the mid-1980s and possibly earlier.

Sinançor Glacier on Mount Verçenik is located at 3,710 m in the Eastern Black Sea Mountains. Kurter (1988) reported 0.14 km^2 of glacier area in the 1970s. We mapped 0.3 km^2 glacier area in the mid-1980s, which we also use for our 1970s area. Thematic Mapper imagery from 1994 found a glacier area of 0.09 km^2 and a WorldView-2 image from 2011 found 0.03 km^2 of glacier ice present at that time. Sinançor Glacier is almost finished and will vanish in the next few years.

Medetsiz Glacier, located at 3,524 m in the Middle Taurus Mountains, was reported by Kurter (1988) to have 0.06 km^2 of glacier area. Our TM images of 8 October 1987, 22 October 1998, and 12 August 2007 were all ice-free, as was a WorldView-1 image from 25 October 2008. This glacier had disappeared at least by the late 1980s and possibly earlier. We were unable to use MSS data from the 1970s for an area determination at that time because the glacier was too small.

Hasanbeşir Glacier on Mount Hasanbeşir, located at 3,503 m in the Kavuşşahap Mountains south of Lake Van in Eastern Turkey, was reported to have an area of 0.06 km^2 in the 1970s. We were unable to detect the presence of any ice in Landsat-3 RBV imagery from 1980 or in TM imagery from 1984, 1987, 1989, 1998, or 2004. We were able to detect 0.10 km^2 of glacier ice in 2011, only by using the very high radiometric and spatial resolution of Quickbird-2 commercial satellite data to map glacier ice in shadows. We also used our 2011 area determination for the 1970s, 1980s, and the 1990s. Unfortunately, Landsat and ASTER data lack the high radiometric and spatial resolution needed to map glacier margins in shadows.

Gedik Glacier, actually several small glaciers, located at 3,368 m in the Mercan Mountains, was determined to have a surface area of 1.6 km^2 in the 1970s, which decreased to 1.4 km^2 in 1984 in the 1980s. These glaciers further decreased to 0.8 km^2 in the 1990s and a WorldView-2 image in 2012 mapped 0.45 km^2 of glacier area. A Landsat-8 image in 2013 independently determined the same 0.45 km^2 area.

Avliyana Glacier on Mount Aptalmusa, located at 3,331 m elevation in the Gavur Mountains near the Black Sea Coast in Northeastern Turkey, was reported by Kurter (1988) to have 0.045 km^2 of glacier

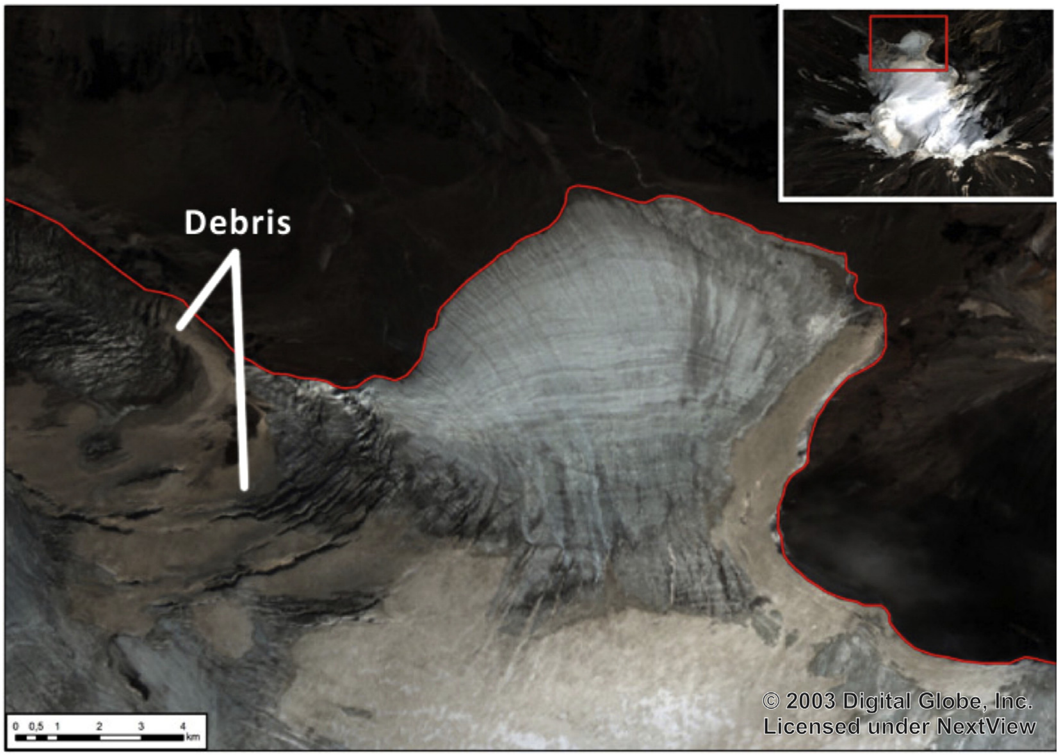

Fig. 5. A blowup of the 2003 Quickbird-2 60 cm pan-sharpened image of Mt. Ağrı. The complete image appears as the upper right insert. Note how the high spatial resolution Quickbird data enable detection of debris-covered areas of Mt. Ağrı. See also Figs. 2 and 5 as well as Table 2. We were able to use commercial satellite imagery from thirteen glacier areas identified by Kurter (1988), Çiner (2004), and Sarıkaya et al. (2011) and found the ≤1 m commercial satellite spatial resolution data invaluable for detecting debris-covered areas and for aiding our verification of Landsat and ASTER image analyses.

area. We detected 0.07 km^2 in 1970s and 1980s with MSS and Landsat-3 RBV. However, we were unable to detect any glacier ice in TM imagery from 1984, 1985, 1987, 1998, or 2007. A WorldView-2 image from 2011 also revealed no ice of any kind. We conclude the Avliyana Glacier had disappeared by the 1980s and possibly sooner.

Karagöl Glacier, located at 3,107 m in the Karagöl Mountain 50 km south of the Black Sea, was reported to have 0.08 km^2 of glacier in the 1970s (Kurter, 1988). We found a glacier area of 0.08 km^2 in 1984, 0.05 km^2 in 1998, both from TM imagery, and 0.04 km^2 using WorldView-2 imagery from 2012.

Our results, summarized in Table 2, were very similar in total glacier area for the 1970s to those of the combined Kurter (1988), Çiner (2004), and Sarıkaya et al. (2011) areas: 25 km^2 vs. 23 km^2, respectively. However, substantial 1970s glacier extent differences were found for Süphan (3.0 vs. 1.3 km^2), Kaçkar (0.1 vs. 1.8 km^2), Geverok (0.8 vs. 1.5 km^2), and Sinançor (0.1 vs. 0.3 km^2), respectively. We were fortunate to be able to use large quantities of TM data, especially from Landsat-5, for the remarkable 27 years this satellite operated from 1984 to 2011. Kurter (1988) and Çiner (2004) only had available Landsat MSS and Landsat-3 RBV imagery and we commend the extensive earlier studies of Kurter with his coworker Prof. Sungur. We conclude from our mapping work that the area of glaciers in Turkey was 25 km^2 in the 1970s, 21.1 km^2 in the mid-1980s, 15.8 km^2 in the mid-1990s, 11.8 km^2 for 2007–2011, and decreased to 10.85 km^2 in 2013-2013.

4. Meteorological data

We complied meteorological information from seven recording locations close to the glacier areas we studied to determine any systematic variations in temperature and precipitation. The Turkish meteorological station locations used were Ağrı, Hakkari, Van, Iğdır, Kayseri, Rize, and Artvin (Table 4). This was necessary to address questions of variations of temperature and precipitation, as these determine glacier growth or recession. While the closest available meteorological stations are not situated on the glacier peaks, we assume the same climatic trends apply to the mountain peaks. We also used the 1° × 1° Global Precipitation Climatology Project (GPCP) data from 1980 to 2012 to evaluate annual and winter precipitation (Fig. 6). We found similar results for the station precipitation data in Table 4 as we found for the 1° × 1° GPCP data from 1980 to 2012 for the same areas. We used cloud cover information from the University of Wisconsin Climate Impacts Group for cloud cover variation for our glacier areas, annually, for the winter months, and for the summer months (Wylie, Jackson, Menzel, & Bates, 2005).

We found no trends in annual average maximum temperatures for the entire respective records from six stations and a slight cooling of −0.02 °C yr^{-1} at one station (Table 4). However, for annual minimum

Table 3
Summary of the most useful commercial satellite data used in our study. We were able to evaluate forty-one high resolution images for thirteen of the fourteen glaciers of Turkey identified in Table 1.

Glacier	Peak elevation (m)	Acquisition date	Satellite
Ağrı	5,137	10 Sept 2003	QuickBird-2
Uludoruk	4,135	25 Sept 2010	WorldView-1
Süphan	4,058	13 Sept 2011	GeoEye-1
Kaçkar	3,932	8 Sept 2011	WorldView-2
Erciyes	3,917	5 Sept 2010	WorldView-2
Geverok	3,794	20 Oct 2010	WorldView-2
Lolut	3,756	25 Oct 2010	GeoEye-1
Sinançor	3,710	11 Aug 2013	Worldview-2
Kırmızıgedik & Avucur	3,562	N/A	N/A
Medetsiz	3,524	30 July 2013	QuickBird-2
Hasanbeşir	3,503	9 Aug 2011	QuickBird-2
Gedik	3,368	14 Sept 2012	WorldView-2
Avliyana	3,331	13 Sept 2011	WorldView-2
Karagöl	3,107	16 Oct 2012	WorldView-2

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Table 4
Summary of ground station precipitation and temperature data used in our study. One station reported a decrease −3.9 mm/yr, while five stations reported precipitation changes of ±1 mm/yr and one station reported a precipitation increase of 2 mm/yr. The temperature data show greater minimum temperature warming than maximum temperatures for both annual temperatures and those for June, July, and August (JJA). We also calculated the maximum and minimum temperature trends from 1970 to 2013 (except for the Rize station with its more limited record), and these appear in parenthesis in bold , i.e., **(0.03)**. We conclude that summer warming and not precipitation or cloud cover variations were responsible for the recession of glaciers. Note the greater rate of increasing minimum temperature, a sign of global warming.

Station	Kayseri	Rize	Artvin	Iğdır	Van	Hakkari	Ağrı
Coordinates (N, E)	38°43′N, 35°29′E	41°02′N, 40°30′E	41°11′N, 41°49′E	44°03′N, 39°55′E	43°21′K, 38°28′E	43°44′N, 37°34′E	43°03′N, 39°43′E
Elevation (m)	1092	8	628	858	1670	1727	1632
Nearest Glaciers	Erciyes, Medetsiz, Lolut	Avliyana, Karagöl	Sinançor, Kaçkar, Kırmızıgedik, Avucur	Ağrı	Süphan, Hasanbeşir	Uludoruk, Geverok	Ağrı
Precipitation							
Years of precipitation record	1931–2011	1930–2006	1949–2013	1948–2012	1939–2011	1951–2013	1947–2013
Mean annual precipitation (mm)	381	2,304	696	255	384	765	516
Annual minimum precipitation (mm), date	258 (2001)	1,600 (1966)	409 (1974)	115 (1970)	235 (2000)	336 (1956)	330 (2008)
Annual maximum precipitation (mm), date	614 (1988)	4,077 (1931)	1,006 (1992)	501 (1963)	543 (1994)	1,331 (1963)	779 (1988)
Trend (mm yr^{-1})	1	−3.9	2	0.9	0.3	0.5	−0.3
Temperature							
Years of temperature record	1931–2013	1930–2006	1948–2013	1940–2013	1939–2013	1963–2013	1940–2013
Minimum annual temperature (°C)	−4.9	6.3	3	−0.7	−2.5	−0.5	−9.2
Minimum temperature trend (°C yr^{-1})	0.03	0.00	0.00	0.04	0.05	0.02	0.02
Maximum annual temperature (°C)	25.4	24.9	25.6	25.4	20.3	20.8	19.8
Maximum temperature trend(°C yr^{-1})	0.00	0.00	−0.02	0.01	0.00	0.01	0.01
Average JJA minimum temperature	5.9	14.9	11.5	11.4	8.8	12.3	5.5
JJA minimum temperature trend (°C yr^{-1})	0.03 **(0.12)**	0.00 **(0.03)**	0.01 **(0.05)**	0.06 **(0.10)**	0.05 **(0.07)**	0.03 **(0.03)**	0.03 **(0.04)**
Average JJA maximum temperature	35.0	29.0	34.5	36.5	31.1	33.1	32.6
JJA maximum temperature trend (°C yr^{-1})	0.00 **(0.03)**	0.02 **(0.05)**	−0.02 **(0.03)**	0.01 **(0.01)**	0 **(0.02)**	0 **(0.02)**	0 **(0.02)**

temperatures, we found a warming of 0.01 to 0.05 °C yr^{-1} at five stations and no trend at one station (Table 4). Upon closer inspection of the temperature data, we found increasing June–August average minimum temperatures of 0.03 to 0.06 °C yr^{-1} at seven stations and no trend at one station, all using the entire station records. The shorter 1970 to 2013 average June–August minimum temperature record show greater increases for all six stations, ranging from 0.03 to 0.12 °C yr^{-1} at all stations (Fig. 7). The surface temperature data in Table 4 and Fig. 7 show conclusively that surface temperatures are increasing in Turkey. Furthermore, a recent study of surface temperature in Turkey has reported a longer growing season and an increased number of days without frost (Erlat & Türkeş, 2012). Similar warming trend of summer minimum temperatures in Turkey have also been reported by other studies. Türkeş et al. (2002) found the majority of meteorological stations in Turkey have been experiencing minimum temperature warming, especially during the warm and dry period of the year. Erlat and Türkeş (2013) reported that statistically significant increasing trends in summer temperatures were not only limited to night-time temperatures but were also observed in daytime temperatures. They found an increasing trend of "summer days" and "tropical days", the

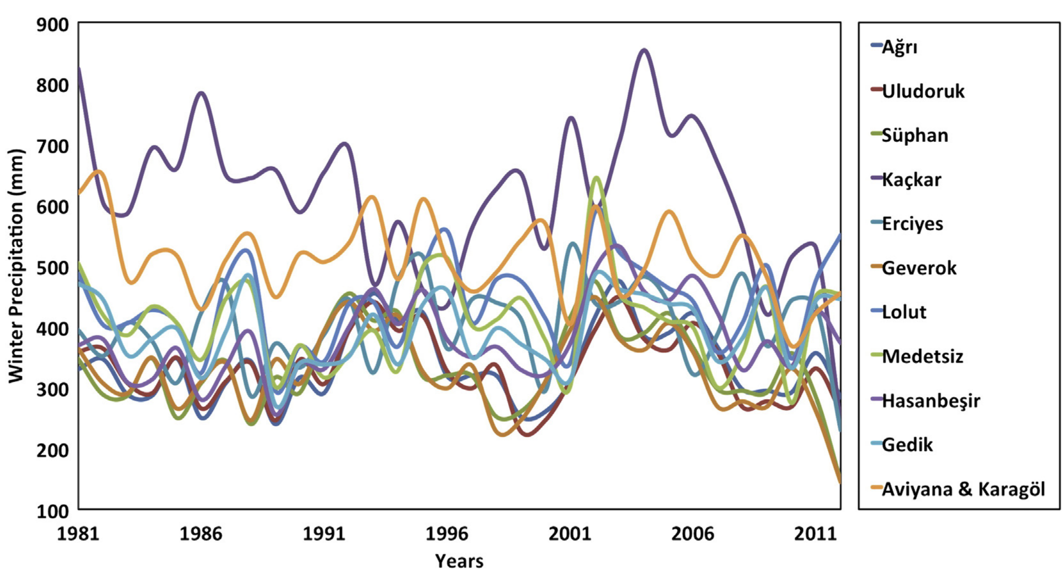

Fig. 6. GPCP data from 1980 to 2012 for one-by-one degree latitude and longitude grid cells containing the fourteen glaciers of Turkey identified by Kurter (1988), Çiner (2004), and Sarıkaya et al. (2011). Four of the cells containing five glaciers had precipitation trends between −1 and +1 mm/yr, two of the cells containing two glaciers had precipitation trends of +3 mm/yr, and three cells containing six glaciers had negative precipitation trends between −7 mm/yr and −3 mm/yr. Note that Sinançor, Kırmızıgedik, and Avucur Glaciers are in the same grid cell with Kaçkar glacier. See also Table 4.

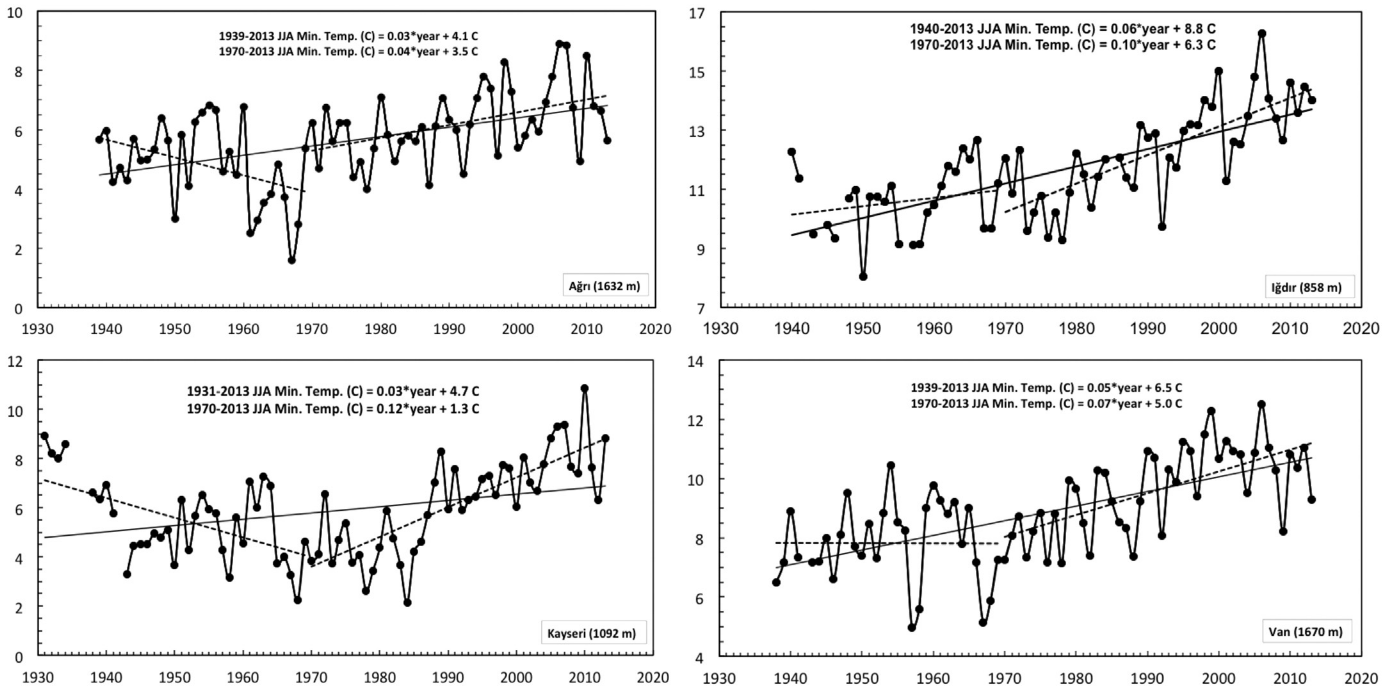

Fig. 7. Average summer daily minimum temperatures from four stations in Table 5. Note the greater increases in the rate of summer warming from 1970 to 2012 than for each of the longer records from these four stations. We attribute glacier recession in Turkey to increased summer daily minimum temperatures in the absence of changes in cloud cover and absence of decreased precipitation. Increasing daily nighttime minimum temperatures are a sign of global warming.

annual number of days with maximum temperature more than 25 °C and 30 °C, respectively, between 1950 and 2010 in their study of 97 meteorological stations in Turkey. They identified the 1950–1975 period of slightly decreasing temperatures, whereas in the period of 1976–2010, there were significant increasing temperatures. Additionally, Zhang et al. (2005) found that the number of "tropical nights" where daily minimum temperatures exceeds 20 °C, has significantly increased not only in Turkey, but also throughout the Middle East. Most of this increase has occurred in the more recent decades.

The precipitation data from the seven stations show a slight -3.9 mm yr^{-1} decrease in precipitation from 1945 to 2012 for one station, a 0.3 to 2.9 mm yr^{-1} precipitation increase for four stations, and two stations with no precipitation variations over this time period (± 0.1 mm yr^{-1}). These results are consistent with other studies, which showed that precipitation, especially winter precipitation, in Turkey did not show a linear increasing or decreasing trend over the same period (Türkeş & Erlat, 2003, 2005). We conclude precipitation decreases were not a factor in glacier recession in Turkey from the 1970s to 2008–2012 (Table 4 and Fig. 7).

We found very minor variations in cloud cover variations from 1979 to 2008, all $\leq 0.1\%$ yr^{-1}, for annual, winter, and summer cloud cover trends from the late 1970s to 2008 (Table 5). We conclude warmer summer minimum temperatures, coupled with no significant variations in precipitation or cloud cover, explained glacier recession in Turkey from the 1970s to 2012–2013 (Fig. 7 and Table 4). Considering the glacier recession, our meteorological data, and previous studies (Erlat & Türkeş, 2013; Zhang et al., 2005) that show warmer summer temperatures, we indicate that the response time of the glaciers in Turkey is on the order of 10 to 30 years.

Field verifications were conducted on Mt. Ağrı in 2011 and on Mt. Erciyes and Mt. Kaçkar in 2012. In August 2011, we attempted a field survey of Mt. Ağrı but encountered heavy snow that limited our verification efforts. In August 2012, we confirmed very little glacial ice remained on Mt. Erciyes and ice that was present was in several very small patches. We also confirmed our analysis of the glacial extent of Mt. Kaçkar was correct by ground verification there. It was impossible to conduct field verifications on Mt. Uludoruk and Mt. Dolampar in the extreme Southeast of Turkey in 2011 and 2012 because the security situation did not allow investigations in these areas. Instead, we used <1 m spatial resolution commercial satellite data from thirteen of the fourteen glaciers in our study, and these data were invaluable for verification purposes, including identification of debris-covered margins, while avoiding potential security problems in Southeastern Turkey for glaciers there.

Table 5
Annual and summer cloud cover data from Wylie et al. (2005) for 1979 to 2008. All numbers are in percentages and the trends are percent/year. Note the lack of any trend in cloud cover for the December to February or for June to August.

Cloud cover	Glacier							
1979–2008	Ağrı	Uludoruk Geverok	Süphan	Erciyes	Demirkazık	Medetsiz	Aptalmusa	Karagöl
Average annual (%)	73%	79%	72%	75%	69%	77%	82%	83%
Annual 30-year trends (% yr^{-1})	−0.1%	−0.1%	−0.1%	−0.1%	−0.1%	−0.1%	0.0%	−0.1%
Average winter (%)	76%	83%	82%	87%	80%	89%	89%	90%
30-year December–February trends (% yr^{-1})	−0.2%	−0.1%	−0.1%	0.0%	−0.2%	−0.1%	0.0%	−0.1%
Average summer (%)	67%	70%	57%	58%	53%	61%	72%	74%
30-year June–August trends (% yr^{-1})	−0.1%	0.0%	−0.1%	−0.2%	0.0%	−0.2%	0.1%	−0.1%

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5. Conclusions

We present a systematic study of all the glaciers in Turkey using seventy-two Landsat scenes five ASTER scenes from 1970s to 2013 and forty-one commercial satellite scenes from 2003 to 2013. Total glacier area in Turkey decreased from 25 km^2 in the 1970s to 10.85 km^2 in 2012–2013, with greater losses at lower elevations. The majority of the Turkey's glacier area is presently concentrated in two of the highest glaciers, both situated on stratovolcanoes. Of twelve smaller glaciers reported to have been present in the 1970s with a total area of 4.9 km^2 at that time, six had vanished by 2012–2013, and the remaining six small glaciers totaled 2.0 km^2 in extent. We found no variations in precipitation or cloud cover that would explain the high rates of glacier recession we observed from the 1970s to 2012–2013. We found increasing surface temperatures, especially elevated summer night-time or minimum temperatures from 1970 to 2013 were a major reason for the 50% loss of glacier area in Turkey over this time period. The use of commercial satellite imagery, in combination with Landsat TM, ETM+, OLI, and ASTER imagery, improved our study of the glaciers of Turkey from 2000s to 2012–2013.

Acknowledgments

We benefited greatly from the earlier work of Kurter (1988), Çiner (2004), Sarıkaya et al. (2011) and the U.S. Geological Survey's *Satellite Image Atlas of Glaciers of the World*. This later work is invaluable for studying glacier trends over time.

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