

## **Small Glacier Area Studies: A New Approach for Turkey**

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**Abstract:** Many regions of Earth have glaciers that have been neglected for study because they are small. We report on a new approach to overcome the problem of studying small glaciers, using Turkey as an example. Prior to our study, no reliable estimates of Turkish glaciers existed because of a lack of systematic mapping, difficulty in using Landsat data collected before 1982, snowpack vs. glacier ice differentiation using existing satellite data and aerial photography, the previous high cost of Landsat images, and a lack of high-resolution imagery of small Turkish glaciers. Since 2008, a large number of < 1 m satellite images have become available at no cost to the research community. In addition, Landsat data are now free of charge from the U.S. Geological Survey, enabling the use of multiple images. We used 174 Landsat and eight high-resolution satellite images to document the areal extent of Turkish glaciers from the 1970s to 2007-2011. Multiple Landsat images, primarily Thematic Mapper (TM) data from 1984 to 2011, enabled us to minimize differentiation problems between snow and glacier ice, a potential source of error. In addition, we used Ikonos, Quickbird, and World View-1 & -2 very high-resolution imagery to evaluate our TM accuracies and determine the area of nine smaller glaciers in Turkey. We also used five Landsat-3 Return Beam Videcon (RBV) 30 m pixel resolution images, all from 1980, for six glaciers. The total area of Turkish glaciers decreased from 23 km<sup>2</sup> in the 1970s to 10.1 km<sup>2</sup> in 2007-2011. By 2007-2011, six Turkish glaciers disappeared, four were < 0.3 km<sup>2</sup>, and only three were 1.0 km<sup>2</sup> or larger. No trends in precipitation from 1970 to 2006 and cloud cover from 1980 to 2010 were found, while surface temperatures increased, with summer minimum temperatures showing the greatest increase. We conclude that increased surface temperatures during the summer were responsible for the 56% recession of Turkish glaciers from the 1970s to 2006-2011.

### **Introduction**

Turkey is located between 36° and 42°N and is mountainous, with an average elevation of 1132 m. Approximately half the country is comprised of mountains and hills, with the highest mountains of Turkey located in the eastern part. Snowfall in winter exceeds 2 m per year in the higher mountain ranges. Climate continentality increases with distance

from the coast to interior. Glaciers exist in Turkey on three stratovolcanoes and on high peaks in the Southeastern Taurus Mountains, the Middle Taurus Mountains, and the Eastern Black Sea Mountains (figure 1). The mountain peaks that host glaciers in Turkey in the 1970s were reported by Kurter (1988) to be: Mt. Kaçkar, Mt. Verçenik, Mt. Aptamusa, 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 (Table 1).

There is limited historical description of glaciers in Turkey before the 1930s. Ainsworth (1842) and Koch (1846) noted the presence of glaciers in the Southeastern Taurus Mountains and Palgrave (1872) noted glaciers in the Eastern Black Sea Mountains. Observations of selected Turkish glaciers were reported by Maunsell (1901), Penther (1905), and Philippson (1906), but there were no systematic attempts to study individual glaciers nor to inventory the glaciers of the entire country until the 1930s. These pre-1930s antidotal accounts provide little useful information on the extent or margins of any of the glaciers, other mentioning that glaciers were present at specific locations.

Starting with Krenek (1932), Leutelt (1935), and Bobek (1940), scientific study of Turkey's glaciers began and continued with the post World War II efforts by Turkish geographers, including Erinç (1949a, 1949b, 1951, 1952a, 1952b, 1953) and İzbırak (1951). Since this time Turkish and foreign scientists have studied the glaciers of Turkey, including Birman (1968). Before 1945, and the subsequent acquisition of vertical aerial photography, there was little information about Turkish glaciers that could be used quantitatively, and no systematic inventory of any glaciers exist.

While post-1945 vertical aerial photography exists, it is difficult to use for Turkish glacier mapping because this was not the objective of these acquisitions. Because of the high elevations of Turkish glaciers, there is frequently confusion between glacier, recent snowfall, even in summer, and clouds. This is exacerbated by the black-and-white panchromatic aerial photography acquired to support topographic mapping projects.

With the launch of Landsat's 1, 2, and 3, beginning in 1972, multispectral scanner (MSS) imagery was collected from all the areas where glaciers exist in Turkey. However, MSS data suffer from several limitations: a spatial resolution of 80 m for MSS images, radiometric resolution of 64 quantizing levels, no ice-cloud discriminating short-wave

infrared spectral band, and limited repeat acquisitions. All of these limitations were corrected with the launch of Landsat-4 in 1982 and Landsat-5 in 1984 with their TM instruments and by Landsat-7's Enhanced Thematic Mapper plus (ETM+) instrument. Not only has there been frequent acquisition of satellite data since the mid-1980s, but the TM's spectral bands and 30 m spatial resolution and the ETM+'s 15-m panchromatic band enable quantitative mapping of all the glaciers of Turkey. Quantitative study of Turkish glaciers was thus possible for the first time starting in 1982, although an aggressive acquisition strategy and an open data policy did not exist at that time. Since 2005-2006, quantitative and systematic studies of Turkish glaciers have proceeded and we report new systematic results using a large quantity of Landsat-4, -5, and -7 data and selected very high-resolution satellite imagery in concert.

Our basis for studying glacier extent in Turkey since the 1970s is Kurter (1988) who used 1:500,000 prints of Landsat MSS 80-m data and Landsat-3 RBV 30-m imagery interpreted photographically. The RBV imaged an entire ground scene instantaneously, and provided greater cartographic fidelity than the MSS. The RBV on Landsat-3 had 30-m pixel resolution and is an excellent data source for glacier studies where these data exist. We started from the work of Kurter (1988) and studied in detail the twelve glaciers identified by this work. By using the powerful combination of many TM and ETM+ images, in combination with selected  $\leq 1$  m satellite images, we were able to quantitatively document the areal extent of all Turkish glaciers for the first time. We also used the high accuracy of the TM and ETM+ mapping capability to guide our analyses of Landsat-1, -2, and -3 MSS images, including analysis of three pairs of simultaneously-collected Landsat-5 MSS & TM imagery for Mounts Ağrı, Buzul, and Süphan. Knowing where glacier ice existed in the 1980s enabled us to better process the 1970s MSS data.

### **Remote Sensing of Glaciers**

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 and ETM+ instruments from 1982 to 2011; and high-resolution imagery from 2003 to 2011 from Ikonos, Quickbird, and World View satellites for our study of glacier extent in Turkey. In addition, the Ikonos,

Quickbird, and World View imagery ( $\leq 1$  m spatial resolution) were extremely useful in mapping several very small glaciers or their remnant fragments, confirm glacial margins detected in TM imagery, and identify debris-covered glacier margins.

When using multi-temporal satellite data, it is critical to ensure all data used are orthorectified to all other images from the same area. This is needed to prevent classification error, where registration errors are confused with glacier recession or expansion. To achieve a very high degree of among-image registration, we obtained the one arc second Advanced Spaceborne Thermal Emission and Reflection Radiometer digital elevation data and used this as the basis for registration of all satellite images. We estimate our orthorectification error to be  $< \pm 30$  m.

It has long been noted that glacier mapping confusion results when snow is present in conjunction with glacier ice. To overcome this we use multiple summer images where possible for every glacier studied and select the minimum snow-cover area per time period. The results of this are in Table 2 and a summary of all the data we used can be found in Appendix Table 1.

We investigated 9 smaller glaciers reported in Kurter (1988), all reported smaller than  $0.8 \text{ km}^2$  in area (table 2), with 7 of those  $< 0.1 \text{ km}^2$ . We acquired Landsat-4 and Landsat-5 TM data for these areas, in addition to acquiring Landsat MSS and Landsat-3 RBV-3 imagery for these glaciers from Landsats-1, -2, and -3. To guide our analyses of MSS data, we analyzed three concurrent MSS-TM acquisitions from Landsat-5. We analyzed a total of 24 Landsat images for the 1970s, 21 images for the 1980s, 28 images for the 1990s, and 101 images for the 2000s, in addition to the eight  $\leq 1$  m spatial resolution images (Table 3).

While there is a clear ice/non-ice difference in spectral reflectance, complications arise when glacier margins are covered by debris. This makes glacier/nonglacier delineation difficult and sometimes impossible. To minimize this problem for data from 2000-2011, we analyzed high-resolution imagery for eight of the twelve Turkish glaciers, where these data were very useful for identifying debris-covered glacial areas. For determinations of areal extent of glacier ice extent in the 1970s, 1980s, 1990s, and the 2000s, we mapped the glacier/non-glacier boundaries as they were evident in the satellite data for all time periods. We acknowledge some errors in our glacier mapping, but use the same methodology for all glaciers for all time periods. Thus we have comparable relative glacier extent information through time.

We assembled the satellite data previously used by Kurter (1988), added additional Landsat data from the 1970s to the Landsat data we have used in the 1980s, 1990s, and 2000s.

## Results

### A. The Major Glaciers of Turkey

#### Mount Ağrı

The ice cap and associated outlet glaciers on Mt. Ağrı, also known as Mt. Ararat, is the highest elevation 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<sup>2</sup>, the same number quoted by Blumenthal (1958). We determined the Mt. Ağrı glacier had a surface area of 8.9 km<sup>2</sup> using MSS data in 1977. TM data from 1987 and 1989 determined its glacier area to be 8.7 and 8.6 km<sup>2</sup>, respectively. TM data from 1998, and ETM+ data from 2000, found glacier areas of 7.1 km<sup>2</sup> and 6.7 km<sup>2</sup>, respectively. Additional TM and ETM+ data found the Mt. Ağrı glacier area in 2004 had decreased further to 6.3 km<sup>2</sup>, decreased in 2006 to 6.0 km<sup>2</sup>, further decreased in 2007 to 5.7 km<sup>2</sup>, and continued its decrease to 5.6 km<sup>2</sup> in 2008. Ikonos data from 2003 gave an area estimate of 6.5 km<sup>2</sup> which compares well to the TM 2003 result of 6.3 km<sup>2</sup> (figure 2).

There is a strong aspect and elevation component to the 1977 to 2008 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 2008 a significant fragmentation occurred at lower elevations with many glacier areas becoming isolated from the contiguous body of the glacier on the southern and southeastern aspects of Mt. Ağrı.

#### Buzul Glacier

In the extreme southeast corner of Turkey lies a portion of the Taurus Mountains that contains Mt. Buzul (also called as Cilo or Uludoruk) and Mt. Dolampar. These two mountains are home to the Erinç and Dolampar glaciers, respectively. The Buzul Glacier, a valley glacier, was reported to have a 1950s surface area of 8 km<sup>2</sup> with a peak altitude of 4,135 m (Kurter 1988). The Buzul Glacier, is assumed to have been contiguous in the recent geological past, but has been fragmented, at least since its first descriptions in the 19<sup>th</sup>

century. The distinct glaciers on Mt Buzul 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 south-east 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 Buzul glacier. (figure 3).

Analysis of MSS data from the Buzul Glacier in 1977 determined a total area of 8.5 km<sup>2</sup>. A generally monotonic decrease in the extent of the Buzul Glacier was found with 6.1 km<sup>2</sup> mapped in 1984, 5.1 km<sup>2</sup> mapped in 1986, 4.7 km<sup>2</sup> mapped in 1987, 4.5 km<sup>2</sup> mapped in 1990, 4.1 km<sup>2</sup> mapped in 1998, 3.9 km<sup>2</sup> mapped in 1999, and 3.0 km<sup>2</sup> mapped in 2007, all from Landsat's TM and ETM+ instrument. A 2006 Quickbird image found Buzul's area to be 3.3 km<sup>2</sup>, very similar to 3.0 km<sup>2</sup> mapped in 2007 from Landsat-5's TM (Figure 3).

### **Mt Süphan**

Mt Süphan, another dormant stratovolcano, is 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. The glaciers on Mt. Süphan were mapped in 1977 with MSS data and totaled 1.3 km<sup>2</sup>. This compares with Kurter (1988) circa 1970 reported area of 3.0 km<sup>2</sup> for the glaciers on this mountain. Using more detailed TM imagery for 1984, we documented a glacier area of 1.1 km<sup>2</sup> that decreased to 0.9 km<sup>2</sup> in 1987. By 1998 the glacier area had decreased further to 0.8 km<sup>2</sup>, and has continued to decrease in extent, falling to 0.7 km<sup>2</sup> in 1999 and 0.5 km<sup>2</sup> in 2000. In 2006 and 2007 we found 0.4 km km<sup>2</sup> glacier area for Mt. Süphan (0.38 and 0.35 km km<sup>2</sup>, respectively) and Quickbird imagery found 0.34 km<sup>2</sup> of glacial extent in 2011 (figure 4).

While figures 2, 3, and 4 present multi-temporal images for the three largest glaciers in Turkey, figure 5 shows the high density of Landsat MSS, TM, ETM+, and high-resolution imagery we used for these glaciers. A high-resolution 2003 Quickbird image of Mount Agri appears as figure 6 and conveys the utility of using these data to map glacier margins and determine where glacier margins are covered by debris.

### **B. The Minor Glaciers of Turkey**

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 0.06 km<sup>2</sup>. Thematic mapper

analyses found 1.8 km<sup>2</sup> of glacier in 1987, decreasing to 1.3 km<sup>2</sup> in the mid-1990s. Our analyses of Kaçkar glacier in 2011 with Quickbird imagery found 0.25 km<sup>2</sup> glacier area. We assume a continued decrease in glacial extent from the mid-1990s to 0.25 km<sup>2</sup> in 2011. The MSS imagery from the 1970s was difficult to use and we have used our 1987 TM value for the 1970s glacier extent. The Kurter's (1988) value of 0.06 km<sup>2</sup> was in error because much of the Kaçkar glacier is covered by debris. This was easy to discern in the 2011 Quickbird image and this image was used to guide our analysis of TM and ETM+ imagery.

Erciyes Glacier is located at 3,917 m elevation on a strato-volcano close to the town of Kayseri. Kurter (1988) reported this glacier to have an area of 0.1 km<sup>2</sup> in the 1970s. This glacier had disappeared by the mid-1990s in our TM imagery and was confirmed by a Quickbird image from 2007. Due to the small size of this glacier, we were unable to use MSS data from the 1970s for an area determination at that time. We assumed this glacier had disappeared by the mid 1980s, as no ice was apparent in our 1988 thematic mapper image.

Dolampar Glacier is located at 3,794 m in the Southeastern Taurus Mountains in the extreme southeast of Turkey close to the Iraq border. While Kurter (1988) reported this glacier to have an area of 0.8 km<sup>2</sup> in the 1970s, we found an area of 1.2 km<sup>2</sup> in 1985, which decreased to 1.0 km<sup>2</sup> in 1994. A 2008 Quickbird image of Dolampar Glacier found 1.0 km<sup>2</sup>. Due to the small size of this glacier, we were unable to use MSS data from the 1970s for an area determination at that time.

Demirkazık Glacier is located at 3,756 m elevation in the Middle Taurus Mountains. While Kurter (1988) reported 0.5 km<sup>2</sup> 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. We conclude this glacier has vanished. Due to the small size of this glacier, we were unable to use MSS data from the 1970s for an area determination at that time.

Verçenik Glacier is located at 3,710 m in the Eastern Black Sea Mountains. Kurter (1988) reported 0.1 km<sup>2</sup> of glacier area in the 1970s. We report 0.5 km<sup>2</sup> glacier area in the mid-1980s that had disappeared by the mid-1990s. Due to the small size of this glacier, we were unable to use MSS data from the 1970s for an area determination at that time.

Medetsiz Glacier, located at 3,524 m in the Middle Taurus Mountains, was reported by Kurter (1988) to have 0.1 km<sup>2</sup> of glacier. Our images of 8 October 1987, 22 October 1998, and 12 August 2007 were all ice-free. This glacier had disappeared by at least the late 1980s.

Due to the small size of this glacier, we were unable to use MSS data from the 1970s for an area determination at that time.

Hasanbeşir Glacier, located at 3,503 m in the Kavuşşahap Mountains south of Lake Van in Eastern Turkey, was reported to have an area of 0.1 km<sup>2</sup> in the 1970s. We found no ice present in the images from 29 August 2006 and 6 September 2009. 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 (Appendix Table 1). We conclude this glacier had disappeared by the mid-1980s.

Aptalmusa Glacier, 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 0.1 km<sup>2</sup> of glacier area. We were unable to detect any glacier ice in MSS imagery from the 1970s and Landsat-3 RBV data from 1980, for an area determination at that time, and the 1 October 1984 image contained snow. No glacier was observed in TM imagery from 1 October 1984, 1 August 1985, 8 September 1987, 22 September 1998 or 1 October 2007 images. We conclude the Aptalmusa Glacier had disappeared by the 1980s and possibly sooner. A Quickbird image from 2011 revealed no ice of any kind.

Karagöl Glacier, located at 3,107 m in the Giresun Mountains 50 km south of the Black Sea, was reported to have 0.1 km<sup>2</sup> of glacier in the 1970s (Kurter 1988). We found a 0.04 km<sup>2</sup> area of ice in a 2008 Quickbird image and were unable to detect glacial ice in TM imagery from 6 September 1984, 15 September 1987, or 28 August 1998.

Our results, summarized in Table 2, were very similar in total Turkish glacier area for the 1970s to those of Kurter (1988): 22.9 km<sup>2</sup> vs. 23.4 km<sup>2</sup>, respectively. However, substantial differences of ~ 100% difference were found for Süphan (3.0 vs. 1.3 km<sup>2</sup>), Kaçkar (0.06 vs. 1.8 km<sup>2</sup>), Dolampar (0.8 vs. 1.5 km<sup>2</sup>), and Verçenik (0.14 vs. 0.5 km<sup>2</sup>), respectively. We were fortunate to be able to use large quantities of TM data, especially from Landsat-5, for the unbelievable 27 years this satellite operated from 1984 to 2011. Kurter (1988) only had available Landsat MSS and Landsat-3 RBV imagery and we commend his earlier studies with his coworker Prof. Sungur (Kurter and Sungur 1980). We conclude from our mapping work that the area of glaciers in Turkey was 23.0 km<sup>2</sup> in the 1970s, was 19.9 km<sup>2</sup> in the mid-1980s, was 14.5 km<sup>2</sup> in the mid-1990s, and was 10.1 km<sup>2</sup> for 2006-2011.

### **Climatic Factors**

We compiled 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 is necessary to address questions of variations of temperature and precipitation, as these affect glacier growth or recession. We also used the 1° x 1° Global Precipitation Climatology Project data from 1980 to 2007 to evaluate precipitation (Table 7). We found similar results for the station precipitation data in table 4 as we found for the 1° x 1° Global Precipitation Climatology Project data from 1980 to 2007 . We also used cloud cover information from the University of Wisconsin for cloud cover variation in Turkey annually, for the winter months, and for the summer months (Wylie et al. 2005).

We found no variations in annual average maximum temperatures for the entire respective records from six stations and a slight cooling of  $-0.03^{\circ}\text{C yr}^{-1}$  at one station (Table 4). However, for annual minimum temperatures, we found a warming of  $0.01$  to  $0.05^{\circ}\text{C yr}^{-1}$  at four stations, no trend at one station, and a slight cooling of  $-0.02^{\circ}\text{C yr}^{-1}$  at one station (table 4). Upon closer inspection of the temperature data, we found increasing June – August average minimum temperatures of  $0.02$  to  $0.06^{\circ}\text{C yr}^{-1}$  at five stations, no trend at one station, and a slight cooling of  $-0.01^{\circ}\text{C yr}^{-1}$  at one station. The shorter 1970 to 2007 average minimum temperature record show greater increases for six stations, ranging from  $0.03$  to  $0.11^{\circ}\text{C yr}^{-1}$ , and a decrease  $-0.01^{\circ}\text{C yr}^{-1}$  for one station (figure 8). The 1970 to 2007 average maximum temperature record show greater increases for six stations over and above the 1930 to 2007 record, ranging from  $0.02$  to  $0.08^{\circ}\text{C yr}^{-1}$ , with no change for the other station. The surface temperature data in Table 4 and figure 8 show conclusively that surface temperatures are increasing in Turkey. Furthermore, a study of surface temperature in Turkey has reported a longer growing season and the number of days without frost (Sensoy 2008).

The precipitation data from the seven stations show a slight  $-3.9\text{ mm yr}^{-1}$  decrease in precipitation from 1945 to 2006 for one station, show a  $0.3$  to  $2.9\text{ mm yr}^{-1}$  precipitation increase for four stations, and show two stations with no precipitation variations over this time period ( $\pm 0.1\text{ mm yr}^{-1}$ ). We conclude that precipitation decreases are not a factor in Turkish glacier recession from the 1970s to 2008-2011 (Table 4 and figure 7).

We found very minor variations in cloud cover variations from 1979 to 2008, all  $\leq 0.1\% \text{ yr}^{-1}$ , 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, explain glacier recession in Turkey from the 1970s to 2008 (figure 7, figure 8, and table 4).

## Conclusions

We present the first systematic study of all the glaciers in Turkey using 174 Landsat scenes from the 1970s to 2011 and eight  $\leq 1$  m high-resolution imagery from 2003 to 2011. Total glacier area in Turkey decreased from 23 km<sup>2</sup> in the 1970s to 10.1 km<sup>2</sup> in 2007-2011, with greater losses at lower elevations. The vast majority of the existing glacier area is presently concentrated in three of the highest glaciers, all situated on stratovolcanoes. Of nine minor Turkish glaciers reported to have been present in the 1950s and 1960s that had a reported total area of 2.0 km<sup>2</sup> at that time, six had vanished by the 1980s and the remaining three totaled 0.5 km<sup>2</sup>. We found no variations in precipitation or cloud cover that would explain the high rates of glacier recession we observed from the 1970s to 2008-2011. We find increasing surface temperatures, especially in the summers from 1970 to 2006, which were the reason for the 56% loss of Turkish glacier area over this time period.

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