

## The Recessions of the Pasterze Glacier, Austria, as seen on Maps, Satellite Imagery, and Measured *in situ* from 1864 to 2008

KLAUS J. BAYR<sup>1</sup> AND DOROTHY K. HALL<sup>2</sup>

### ABSTRACT

Many glaciers in Europe have been receding since 1928 (or before). Several scholars have used satellite imagery to determine the recessions of the glaciers. Problems with such attempts that have been demonstrated include difficulty in distinguishing between terminal moraines and the actual glacial ice since some ice is covered with glacial till. It is always necessary to back up the findings of satellite imagery with ground truth. Maps of the Austrian glaciers, dating back to 1864 can be used to determine the former positions of glacier termini, though the errors may not be specified. While the dates of such maps might not reflect the exact location of the terminus in that year, it is the only credible record available for these early years. We digitized the terminus of the Pasterze Glacier, Austria, from maps and transferred these lines onto a recent map and/or satellite image. In recent years, the use of GPS measurements and, a laptop computer in the field using the GIS program, IDRISI, and the digital maps of the Alpenvereinskarte (map) have made it possible to record the precise position of the terminus while walking along the terminus. This paper demonstrates graphically the location of the Pasterze Glacier terminus from 1864 to 2008 using the methods described above.

**Keywords:** Pasterze Glacier, IKONOS, Landsat, Global Positioning System, Geographic Information Systems

### INTRODUCTION

In general, glaciers on Earth have been retreating during the last two centuries, though there have been some advances. The glaciers in Europe are no exception. One of these glaciers is the Pasterze located in the Eastern Alps in Austria. It is the longest glacier the Eastern Alps with a length of 11.0 km in 1852 and 9.5 km in 1969 (Wakonigg and Lieb, 1996). Since 1969 it has had even more significant losses not only in length but also in thickness and width. This glacier has been surveyed for many years by a research group of the University of Graz and others (Lieb, 2008). One of us (KJB) first visited the glacier in 1969 and has since continued to obtain ground truth measurements of the terminus on an intermittent basis. In addition, several Landsat, SPOT (2008) and Ikonos (2001) images have been studied to augment and verify the ground observations. Before the onset of the Landsat satellite series, air photos and topographical maps were used to determine the location of the terminus.

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<sup>1</sup> Keene State College, 9 Monadnock Court, Keene, NH 03431, kbayr@keene.edu

<sup>2</sup>NASA, Goddard Space Flight Center, Code 614.1, Greenbelt, MD 20771, dorothy.k.hall@nasa.gov



Figure 1. Location of the Pasterze Glacier.

## BACKGROUND AND METHODOLOGY

The Pasterze Glacier (47° 6' N, 12° 42' E) flows from the Johannisberg (3463 m) and is located in the Hohe Tauern Range which is part of the Eastern Alps of Austria and extends east of the Rhine River (Fig. 1). The highest peak in Austria, the Grossglockner (3798 m), is located to the southwest of the Pasterze and its hanging glaciers contribute ice and morainic material to the Pasterze.

Maps from 1864, 1876, 1893, 1928, 1965, 1985 and 2002 were studied. In addition, much satellite data have been analyzed: Landsat MSS images from August 26, 1976; Landsat TM images from August 3, 1984, August 9, 1986, August 6, 1988, August 4, 1990 and August 1, 1992; Landsat ETM+ images from July 22, 2000 and August 26, 2001; an Ikonos image from October 03, 2001, and a SPOT image from September 17, 2008. Ground truth measurements were taken every year since before WWII by a team from the University of Graz.

A great deal of work has been done on the Pasterze Glacier, some of which is discussed below. In addition, we have been studying the Pasterze Glacier using satellite data since the late 1980s, using Landsat data dating back to 1976. We measured changes in the Pasterze and the nearby Kleines Fleisskees (see Hall et al., 1992 and Bayr et al., 1994). Detailed study of the Pasterze using available ground, meteorological and satellite data is described in Bayr et al. (1994), and errors inherent in mapping historical glacier positions (using maps and satellite data) are discussed in Hall et al. (2003).

The maps of 1864, 1876 and 1928 show the location of the terminus and its changes in location, though the map errors are not specified. The Landsat and the Ikonos images are excellent tools for showing the location of the till-free part of the Pasterze ice tongue, the till-covered part of the glacier cannot be distinguished because the till has the same signature as the surrounding rock and moraine material that is produced by the glacier as it thins. It is therefore necessary to conduct ground truth measurements to determine the full extent of the ice tongue since such a large percentage of it is till-covered. A team of two to three people, led by one of the authors (KJB) used Garmin III plus units to collect the location of UTM points. Later a laptop computer with an attached GPS was used to record the path on Landsat TM scenes but we reverted in 2005 to the use of a GPS 76S unit without the attached laptop and then transferred the UTM points onto the Landsat and Ikonos scenes.

Over the years it has become increasingly difficult to measure the exact extent of the ice tongue in the field because of the greater discharge of water and the resulting speed and deeper water,

caused by accelerated melting of the glacier. This has resulted in deeper and wider crevasses and the creation of a deeper and wider stream between the till-covered and till-free parts of the glacier. Another problem that has been encountered deals with the reception of the GPS points; the narrow U-shaped valley limits the satellite transmission and thus the accuracy of the UTM points especially near the southwest walls of the glacier valley is compromised.



Figure 2. Map of the Pasterze tongue in 1864.

## RESULTS

The use of maps and satellite imagery combined with ground truthing is a valuable way to determine the location of the terminus of the Pasterze. The 1864 map (Fig.2) clearly shows the extent of the terminus beyond what are today the Margaritze reservoir and the tributary hanging glaciers on both sides. At that time they were still connected to the glacier tongue.

Since 1880 the Pasterze glacier has lost almost 1300 m in length and is now approximately 8 km long. This was calculated by adding the average losses per year measured by the research teams and location of the terminus on the maps. G.K. Lieb (1992/93) states that the Pasterze has lost 1900 m from 1850 to 1969.

If one measures the location of the terminus on the 1893 map and compares that to the location of the GPS points of 2008, the actual loss is 2,138 m (Fig. 3). The average rate of recession between 1880 and 2008 was 10.72 m per year. Between the years of 1910 and 1934 the average loss was only 2.51 m per year with slight advances in three years: 1910, 1926 and 1934. Between 1982 and 2008 the average rate of recession increased to 18.77 m per year (Fig. 4). Through digitizing the area of the tongue in the GIS software IDRISI, we find that the 2008 data show a loss of approximately 62% compared to the 1893 map (Figs. 5, 6 and 7). Wakonigg (1999) measured the Pasterze tongue in 1985 as being 4.09 km<sup>2</sup>. Connected with this was a great loss of volume and thickness of the glacier. By 1928 – one of the recent years of small advances – the tongue area had lost only 9% of its area as compared to its 1893 extent.

### Recession of the Pasterze from 1880 to 2008 in meters

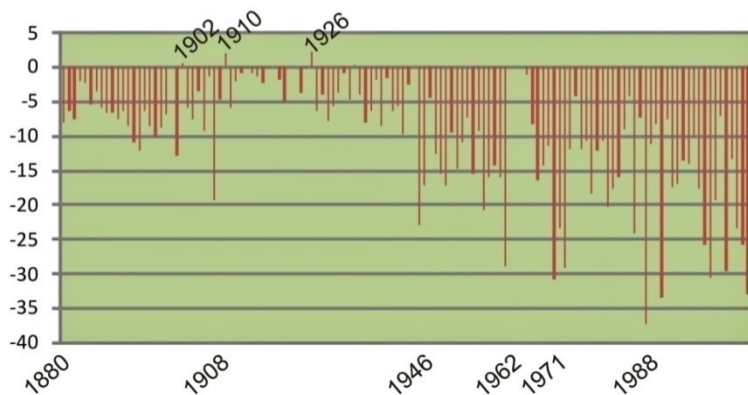


Figure 3. Recession of the Pasterze from 1880 to 2008 in meters.

### Recessions of the Pasterze from 1970 to 2008 in meters

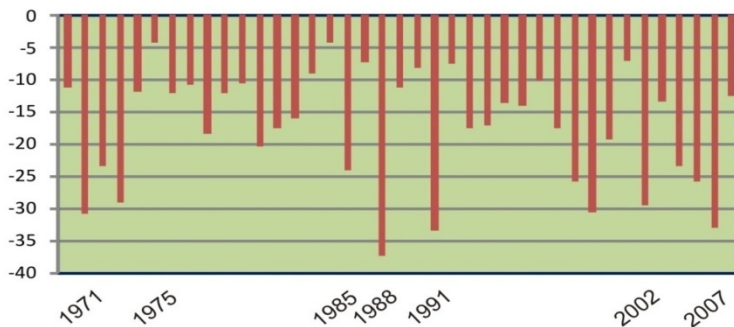


Figure 4. Recession of the Pasterze from 1970 to 2008 in meters

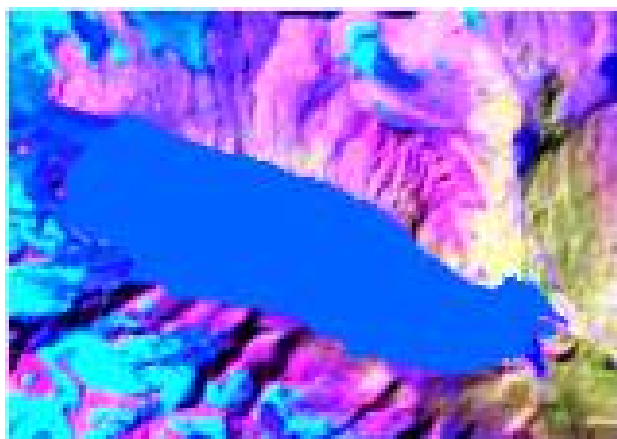


Figure 5. Extent of the tongue area in 1893.

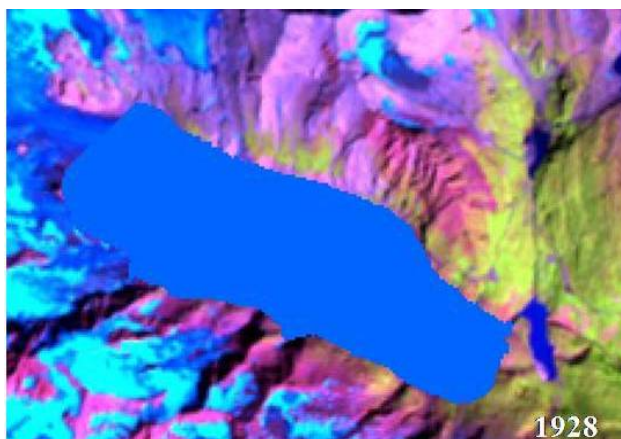


Figure 6. Extent of the tongue area in 1928.



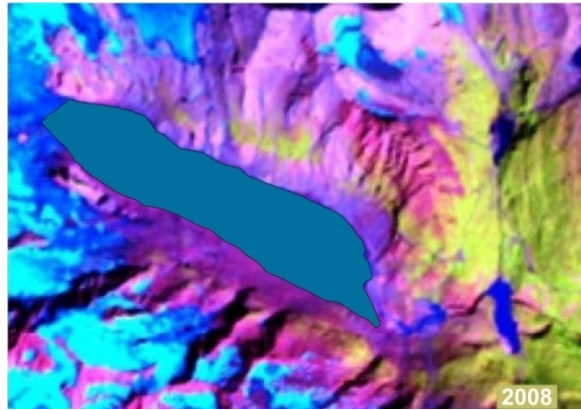


Figure 7. Extent of the tongue area in 2008.

Using the data from the maps and our own data collected through ground truthing, the limits of the terminus were drawn on the Alpenvereinskarte (map) of 2002. The glacier not only receded in length but also shrank in width. Our data also show clearly that the till-free part of the glacier receded a longer distance than the till-covered part. In the early 1990s the width of the lateral moraine covered part of the glacier measured approximately 400 m.

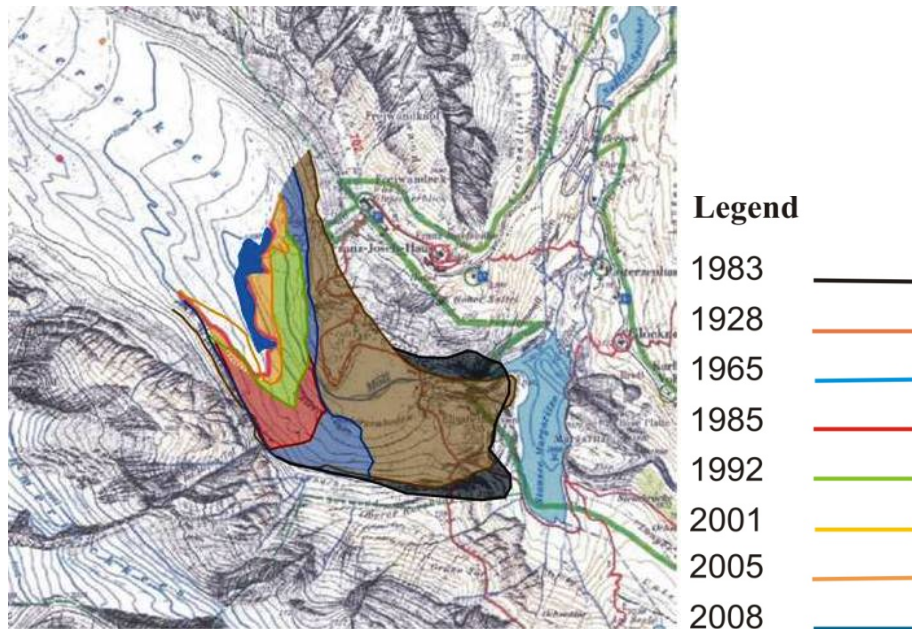


Figure 8. Recessions of the Pasterze Glacier tongue from 1893 to 2008 superimposed on the Alpenvereinskarte (map) of 2001.



Figure 9. The Pasterze Glacier of 2008 (left) and 1969.

By comparing the pictures in Figure 8 one can see that the glacier tongue has receded dramatically. These pictures were taken from two different vantage points approximately 200 m apart. By looking at the Johannisberg (highest mountain in the back on right) the bedrock becomes visible at the icefalls in the accumulation area in 2008. Also, the truncated spur of the Kleine Burgstall to the left of the Johannisberg has a much greater exposure in 2008 than in 1969. Furthermore, one can see the change of the ice in length and volume of the hanging glaciers on the left-hand side. The till-free part of the glacier is much smaller in width in 2008 as compared to 1969. There was no usable satellite image available from 2002 to 2008. The SPOT image of September 17, 2008 proved to be unusable because of the fresh snow cover beyond the lower part of the terminus thus making it impossible to see the terminus.

## CONCLUSIONS

Globally, glaciers have receded over the past 150 years and glaciers in the European Alps have lost more than 50% of their volume (Haeberli et al. 2000). The Pasterze Glacier has receded dramatically since 1864 in response to an increase in air temperature, particularly summer temperature (Bayr et al. 1994).

It is difficult to accurately measure the area of the Pasterze terminus by remote means alone, because a large part of the tongue is covered by morainal material. Between 1984 and 2000 the glacier terminus receded  $303 \text{ m} \pm 40 \text{ m}$  (at an average rate of 18.9 m) according to Landsat-derived measurements while ground data from the same period show a recession of 290 m. Our data show clearly that the till-free part receded a longer distance than the till-covered part. Adding the ground data from 2002 to 2008 to the satellite data a loss of 467.5 m (average rate of 19.47 m per year) is seen while ground data from the same period show a recession of 454 m (at an average rate of 18.91 m). Though there was no usable satellite data available to us after 2001, we show that combining ground truth and satellite measurements provides a good way to accurately measure glacier changes. The use of old maps, even with unknown errors, combined with in situ and satellite data extends the record of useful measurements on the Pasterze Glacier back nearly 150 years. Globally, there are very few glaciers that have been studied in this kind of detail for such a long period of time.

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