Changes in the Pasterze Glacier, Austria, as Measured from the Ground and Space

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ABSTRACT

Satellite data are used to measure the shrinkage of the tongue of the Pasterze Glacier, a valley glacier located in the Austrian Alps. Summer Landsat satellite data from the following years have been analyzed: 1976, 1984, 1986, 1988, 1990, 1992 and 2000. Ikonos satellite data from 2000 are also shown. Between 1984 and 2000, Landsat-derived measurements show a recession of the glacier terminus of 303 ±40 m, while ground data from the same period show a recession of 290 m. When the glacier position was measured using Landsat data acquired only two years apart, the measurement uncertainty was often close to or greater than the terminus recession, however, when images were spaced more than ten years apart, the terminus recession was far greater than the measurement uncertainty.

Key words: valley glaciers, glacier-terminus changes, Austrian Alps.

INTRODUCTION

There has been a general recession of glaciers in the European Alps since the Little Ice Age ended around 1850, though the recession has been interrupted a few times by brief advances. The glaciers are receding in response to a regional climate warming.

The Pasterze Glacier is in the Hohe Tauern, a mountain range in the eastern Alps of Austria where the Johannisberg (3463 m) and Grossglockner (3798 m) mountains are located. The Grossglockner is the highest peak in Austria from which some tributary glaciers flowing into the Pasterze. In this paper, we discuss historical ice-front positions of the Pasterze, show satellite images, and provide measurements of ice-front position changes from ground and satellite data.

BACKGROUND

A major advance of glaciers in the Austrian Alps occurred around 1600. The glaciers remained in an advanced position, with only small variations for the next 250 years. Most glaciers in the eastern part of the Alps reached another maximum in the 1770s, and again around 1850. Since then, at the approximate end of the Little Ice Age, glaciers receded until about 1965, although there were small readvances between 1890 and 1920. Most of the glaciers stopped advancing in the mid-1980s due to warm summers and reduced snowfall. In 1988, about 80 percent of the Austrian glaciers were in

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recession (Rott, 1993). Böhm (1986) and Bayr et al. (1994) show that there was a general increase in average (May through September) temperature and a concurrent decrease in the number of days between May and September with snowfall since 1886.

There are 925 glaciers with a total area of 542 km^2 in the Austrian Alps, only five of which are larger than 10 km^2; the majority is smaller than 1 km^2. The Pasterze Glacier is the largest with an area of 19.8 km^2, and a length of 9.2 km in 1969 (Rott, 1993). Between 1979 and 1989, the mean equilibrium-line altitude (ELA) of the glacier was 2880 m a.s.l. (Zuo and Oerlemans, 1997).

The terminus of the Pasterze Glacier has retreated each year since the winter of heavy snow in 1965-66, the total cumulative recession as measured on the ground being 408 m (Österreichischer Alpenverein, 1999-2000). Previous work showed that between 1984 and 1990, the terminus of the glacier receded at an average speed of 15 m $year^{-1}$ according to measurements made using Landsat multispectral scanner (MSS) and thematic mapper (TM) data, for a total recession of 90 m. Ground measurements showed a total recession of 102-m over that same six-year period (Hall et al., 1992; Bayr et al., 1994).

Zuo and Oerlemans (1997) used a one-dimensional ice-flow model to conduct a sensitivity experiment on the Pasterze Glacier and to simulate the ice-front variation. Their results show that the glacier has been in a non-steady state from about 1826 to the present, and has a volume response time of 34-50 years. They also projected the behavior of the Pasterze Glacier over the next 100 years under various climate scenarios. According to their model, by the year 2100, the total recession could range from 3 to 5 km, with a total loss of ice volume of 40-63%, if the rate of regional climate warming continues to increase. However, if the future climate remains the same as the mean condition over the last 30 years, the recession of the glacier will be much less.

Satellite Data

The Landsat MSS was first launched in July 1972 on board the Landsat-1 satellite, providing images of the same point on the Earth once every 18 days, cloud-cover permitting, at a pixel resolution of approximately 80 m, in four spectral bands in the visible and near-infrared parts of the electromagnetic spectrum. The TM sensor was first carried on the Landsat-3 satellite in 1982 with a 16-day repeat cycle. It provides 28.5-m pixel resolution images of the Earth's surface in seven spectral bands, ranging from the visible to the thermal-infrared part of the spectrum. The Enhanced Thematic Mapper plus (ETM+) http://landsat.gsfc.nasa.gov/project/satellite.html was launched on the Landsat-7 satellite in 1999; it has eight discrete bands ranging from 0.45 to 12.5 μm; the spatial resolution ranges from 15 m in the panchromatic band (0.52-0.9 μm), to 60 m in the thermal-infrared band (10.4-12.5 μm). All of the other bands have 30-m resolution. Landsat data cover an area 185 km on a side.

The Ikonos-1 satellite was launched on September 24, 1999 by Space Imaging. Ikonos collects, simultaneously, 4-m resolution multispectral data in blue, green, red and near-infrared bands located at: 0.45-0.90 μm, 0.52-0.60 μm, 0.63-0.69 μm, and 0.76-0.90 μm, respectively, and 1-m resolution panchromatic imagery. The Ikonos data cover an area that is nominally 11 km on a side.

METHODOLOGY

We have used Landsat scenes from 1976, 1984 (Figure 1), 1986, 1988, 1990, 1992 and 2000 (Table 1). We also obtained other Landsat scenes (from 1973, 1981 and 1999), but these were not suitable for detailed analysis due to either the presence of new snow cover, cloudcover or cloud shadows obscuring the glacier terminus.

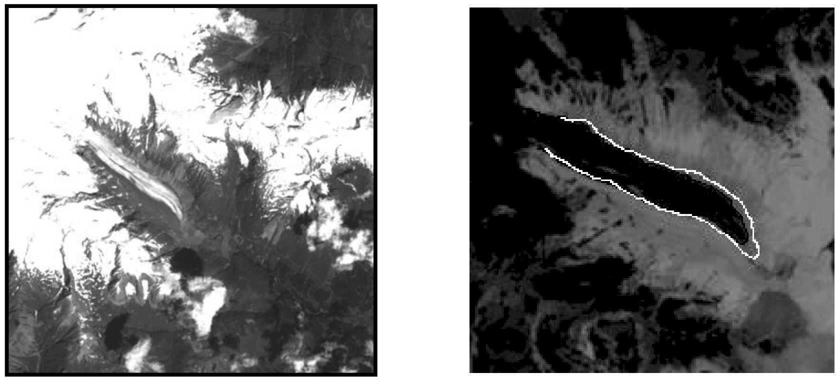

Figure 1. Left - Landsat thematic mapper (TM) image (band 2) of the Pasterze Glacier (August 3, 1984). Right – TM-derived image from July 22, 2000 showing the extent of the glacier tongue using the normalized-difference snow index (glacier tongue is black). Also shown is the 1984 position of the glacier tongue, as measured using Landsat data (white line).

Table 1. Landsat and Ikonos data used in this paper.

Sensor	Date	Path/Row	Scene I.d. #
Landsat MSS	August 26, 1976	206/27	8D20602776239
Landsat TM	August 3, 1984	192/27	LT5192027008421610
Landsat TM	August 9, 1986	192/27	LT5192027008622110
Landsat TM	August 6, 1988	192/27	LT4192027008821910
Landsat TM	August 4, 1990	192/27	LT5192027009021610
Landsat TM	August 1, 1992	192/27	LT4192027009221410
Landsat ETM+ Ikonos	July 22, 2000 September 27, 2000	192/27	LE7192027000020450

All of the Landsat scenes, and the Ikonos scene in Table 1 were registered digitally to the 1984 scene (which is used as the "base") with a pixel resolution of 28.5 m. By registering the scenes to a common base, it is possible to measure changes of the terminus position and other features of the glacier (i.e., the glacier width and the approximate position of the snowline) between years. This has been done previously by Hall et al., 1992 and Bayr et al., 1994, and many by other authors (e.g. Dowdeswell and Collin, 1990; Williams et al., 1997; Lliboutry, 1998). To register scenes, about 100 ground control points (GCP) or points in common between the 1984 and the other images, were determined from both images and saved as a "GCP file." Then a registration routine (which uses a curve-fitting technique), was used to overlay the satellite images (and a 1982 topographic map (Deutscher Alpenverein, 1982)) onto the 1984 Landsat image which was used as the base image. A second-order polynomial was used to warp each image to the 1984 base image.

To improve the contrast between the ice and surrounding areas, the normalized-difference snow index (NDSI) (Hall et al., in press) was calculated for the TM and ETM+ scenes. This involves taking the normalized difference of a visible and a short-wave-infrared band, and is calculated as follows, using TM data:

$$\text{NDSI} = \frac{\text{TM2} - \text{TM5}}{\text{TM2} + \text{TM5}} \qquad [1]$$

where TM2 is TM band 2 (0.52 – 0.60 μm), and TM5 is TM band 5 (1.55 – 1.75 μm). The NDSI value is then multiplied by 100 and then 100 digital counts are added in order to make the NDSI image brighter and thus enhance the contrast between bare ice and the surrounding moraine. An example is shown in Figure 1. Determination of the image coordinates of the terminus, and thus changes in the terminus position to an accuracy of about one pixel could be measured digitally. This technique was used to measure the glacier terminus position from 1984-2000. Then terminus-position changes could be calculated.

In this paper, we also show the temperature (from 1887 to 2000) and precipitation (from 1927 to 2000) data from the Sonnblick Observatory which is located about 15 km east of the tongue of the Pasterze.

RESULTS

Recession of the Pasterze Glacier terminus and narrowing of its tongue were measured using Landsat data from 1984 to 2000, and are shown in Figure 1. Recession of the Pasterze tongue has been measured in the field since 1889 (Wakonigg, 1991; Österreichischer Alpenverein, 1999-2000) (Figure 2). Temperature data from Sonnblick (seen in Figure 3) show that there is an increase in average annual temperature, and spring/summer (May through September) temperatures since the 1880s. The increasing spring/summer temperatures are particularly important in the context of the glacier recession. Precipitation data (Figure 3) show a trend toward decreasing precipitation since the 1970s. A detailed discussion of climate variability and glacier recession in the Austrian eastern Alps can be found in Schöner et al. (2000).

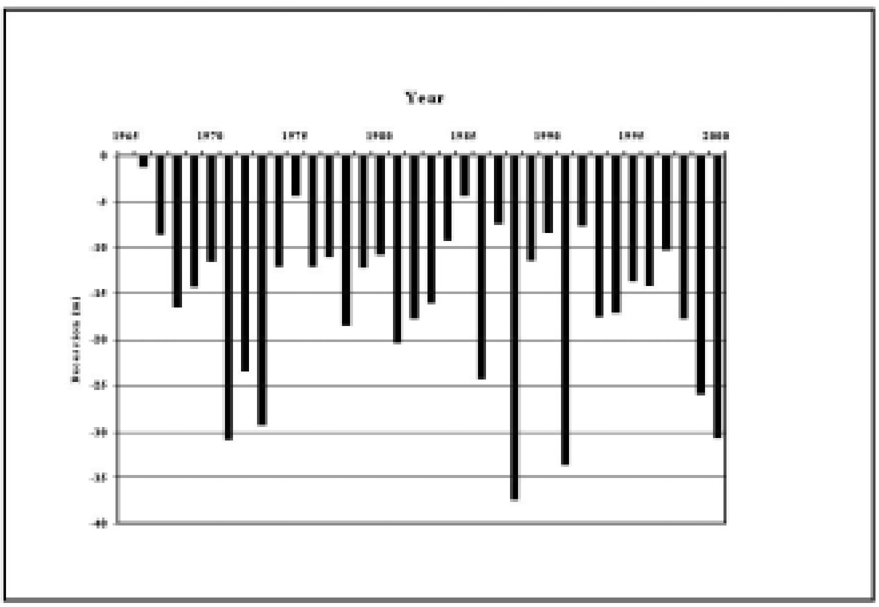

Figure 2. Recession of the Pasterze Glacier tongue as measured on the ground (Österreichischer Alpenverein, 1999-2000).

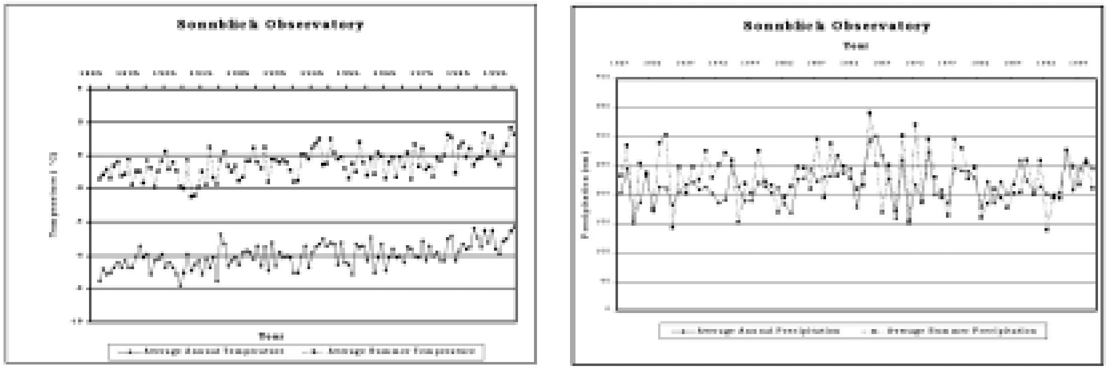

Figure 3. Left - average annual and average spring/summer (May through September) temperature (in °C) from the Sonnblick Observatory, Austria, 1887-2000. Right - annual total and spring/summer total (May through September) precipitation (in cm) from the Sonnblick Observatory, Austria, 1887-2000.

The average rate of recession, as measured from the Landsat data during this period is 18.9 m year^{-1}. The total recession of the Pasterze as measured from satellite data is 303 ±40 m, from 1984 to 2000, while the recession measured on the ground is 290 m (and the error is not reported but is probably ~±1m). If each terminus position is uncertain to 28.5 m (one ETM+ pixel), and the two terminus position measurements are independent, then:

$$\text{Uncertainty} = \sqrt{(28.5^2 + 28.5^2)} \qquad [2]$$

Another source of error, in terms of the comparison of ground and satellite data, is that the measurement from the satellite may not be done in exactly the same place as the measurement on the ground.

An Ikonos image acquired on September 27, 2000 is shown in Figure 4. The spatial resolution of this image is 4 m or 1 m (Figure 4). Fine-resolution imagery is excellent for detailed mapping of the glacier tongue, and is useful for measuring the position of the snowline. The value of these high-resolution data will increase as more years of the data become available. Figure 5 shows a comparison of the ETM+ band 8 15-m resolution image of the Pasterze tongue, with the Ikonos 1-m resolution image of the same area.

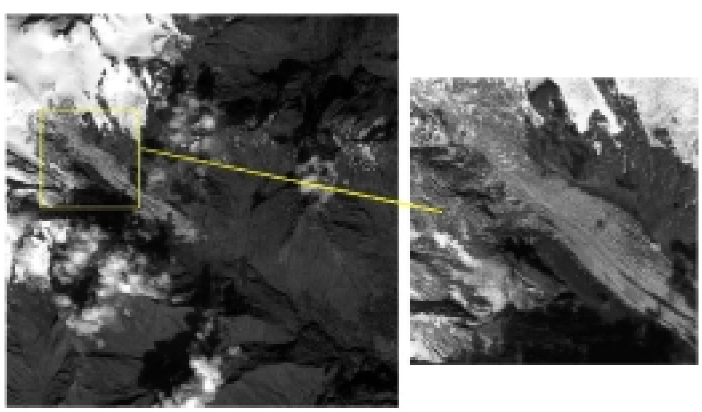

Figure 4. Left - Ikonos image (15-m resolution) of the Pasterze Glacier tongue acquired on September 27, 2000. A subset of the same image, but at 1-m resolution.

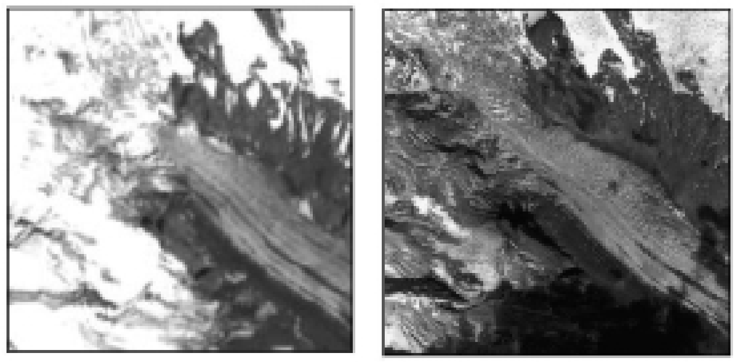

Figure 5. Comparison of the ETM+ band 8 (panchromatic band) 15-m resolution image (left) of the Pasterze tongue, with the Ikonos 1-m resolution image (right) of the same area.

DISCUSSION AND CONCLUSION

It is sometimes impossible to measure, accurately, the position of a glacier terminus from space. This was demonstrated in Williams et al. (1997) in a study of glacier changes on Vatnajökull, Iceland, using Landsat data. When a glacier is in recession, often debris will collect on the surface of part or all of the glacier tongue and the glacier will have a reflectance that is similar to that of the surrounding moraine. This can make the terminus position difficult to locate, especially from space. On the ground, the terminus position can often be determined by digging into the top layers of the debris. If ice is found, then that may represent the position of the terminus, although stagnant ice, unconnected to the glacier tongue may also be revealed. With the Pasterze Glacier in the 1970s, it was not possible to determine the extent of the tongue using Landsat imagery. Field measurements showed that the tongue was much larger than it appeared in the imagery (in the 1970s) because part of the tongue was covered with a thick layer of debris. As the glacier tongue shrank, some of the debris-covered ice melted.

We did not use the Landsat satellite image from 1976 to measure the glacier-terminus position because it did not reflect the actual terminus position on the ground. On the southwestern side of the glacier, the terminus was covered by thick debris while the northeastern part was debris-free. The difference between those two parts of the glaciers is less obvious today (due to melting) than it was in the 1970s and before. By the early 1980s, the ice shrank away from some of the debris according to ground measurements. A 1982 topographic map (Deutscher Alpenverein, 1982) was digitally registered to the satellite image. The map was constructed originally in 1928 using stereographic air photos, and updated in 1953, 1965, 1969, 1973 and 1982. The glacier positions, shown on the 1982 map, were determined in 1965 using stereographic air photos. However, in 1965, as determined from the map, the glacier tongue occupied a much larger area than it appeared to in the 1976 Landsat image. Though this was 11 years later, reports from the field show a terminus shape (in the mid 1970s) similar to that shown on the map.

Measurements reported in Hall et al. (1992) and Bayr et al. (1994) were somewhat different from the measurements reported in this paper. The use of the NDSI enabled good delineation of the bare-ice surface of the glacier tongue. In previous work, false-color composite images, or a ratio of TM bands 4 and 5 were used. The NDSI provides a sharper image of the boundary between the glacier tongue and the surrounding moraine, and permits more accurate intercomparison of the bare-ice part of the glacier tongue positions in different years.

The measurement error often exceeded the amount of recession when only two years intervened between images. However, when ten or more years had elapsed, the uncertainty of the measurements was less than the total recession. The position of the terminus may be measured using a variety of techniques, including the NDSI method. The Landsat database, beginning in 1972, enables decadal-scale glacier changes to be measured and is an important resource for measuring glacier changes and correlating those changes with regional climate changes in some places on the Earth.

From 1984-2000, ground measurements show that the Pasterze Glacier tongue receded 290 m. Measurements using Landsat TM and ETM+ data show a recession of 303 ± 40 m. Though the ground measurements are more accurate than are the satellite measurements, it is clear that the Landsat measurements are useful for monitoring glaciers in the context of regional climate change. However, local knowledge of the position of the glacier tongue is extremely useful and increases the accuracy of the satellite measurements. Ikonos data with up to 1-m pixel resolution have a great potential for measurement of glacier changes as data from other years become available in the future.

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