DETERMINATION OF GLACIER MASS BALANCE CHANGE USING THEMATIC MAPPER DATA

Dorothy K. Hall

Hydrological Sciences Branch
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

Klaus J. Bayr

Geography Department
Keene State College
Keene, NH 03431

William M. Kovalick

Science Applications Research Corporation
Lanham, MD 20706

ABSTRACT

The Pasterze Glacier is part of the Grossglockner system of glaciers and is located in the eastern Alps of Austria. For the last few hundred years, glaciers in this area have generally been retreating. The terminus of the Pasterze has retreated 317 m since 1965, for example. Using Landsat Thematic Mapper (TM) data, the extent of melting on the glacier was measured using 03 August 1984 and 09 August 1986 TM scenes on an interactive image analysis computer with images produced from the ratio of TM band 4 to TM band 5. The size of the glacier was measured and it was determined that the area of melting covered 20.8% of the total area in 1984 versus 34.7% of the total area in 1986. At-satellite reflectance maps of the Pasterze Glacier in 1984 and 1986 have also been computed using Landsat TM data. Though these TM-derived reflectances are generally thought to underestimate reflectance due to atmospheric effects, trends in reflectance are consistent with the increased amount of melting in 1986 as compared to 1984. The average reflectance of the glacier was lower in 1986 (52.2%) as compared to 1984 (60.2%). If large-scale retreat of glaciers occurs, it will result in lowered average regional albedo thus permitting greater absorption of incident solar radiation if ablation areas expand thus enhancing melting in glacierized areas.

Introduction

The mass balance of valley glaciers is integrally linked to regional and global climate. Recent work has shown that the small glaciers of the world (including valley glaciers and ice caps) may have contributed up to 50% of the meltwater to the observed sea level rise during the last century (Meier, 1984). Though this widespread glacier melt has been documented in many areas of the world, recent studies show that some regions may now be experiencing glacier advances and thus a trend toward a positive mass balance (Mayo and Trabant, 1984). The Landsat series of sensors has been recording changes in glaciers over a period of 16 years. One glacier system that has been experiencing significant retreat is the Grossglockner in the eastern Alps of Austria. In this study, we employ two years of Landsat Thematic Mapper (TM) data to study the Pasterze Glacier which is within the Grossglockner system of glaciers, and to measure changes in the reflectance of the glacier system between years as an indication of glacier mass balance.

Background and Study Area

Landsat Multispectral Scanner (MSS) data have been acquired since 1972. The MSS sensors have 80 m pixel resolution and operate both in the visible and near-infrared parts of the electromagnetic spectrum. In 1982, Landsat-4 was launched with a TM on-board in addition to the MSS. The TM has additional bands relative to the MSS, and 30 m resolution for all except the thermal band (TM band 6) which has a resolution of 120 m.

Landsat MSS data have been employed to measure the position of the snow line on glaciers and, if measured at the end of the melt season, the position of the equilibrium line. The equilibrium line is the line that separates that portion of a glacier having a net gain of mass over the year from that portion showing a net mass loss (Paterson, 1981). Ostrem (1975) has used MSS data to locate the equilibrium line and to define a relationship between the height of the equilibrium line and net mass balance of the Nigardsbreen Glacier in Norway. Meier (1973) has shown that the accumulation area ratio (AAR) of a glacier can be measured using Landsat data. The AAR is the area of accumulation of a glacier at the end of the summer divided by the area of the entire glacier (Paterson, 1981). Additionally, Landsat data are useful for measuring glacier advance or retreat through analysis of the position of the glacier terminus and surface reflectance (Hall et al., in press).

Assessment of the mass balance of glaciers can also be accomplished through analysis of the glacier facies. A glacier may display up to four distinct facies : the ice facies which comprises the ablation area, and the wet-snow, percolation and dry snow facies which are located in the accumulation area (Benson, 1962; Benson and Motyka, 1979). Most temperate glaciers do not display all four facies. Because the facies often have different reflectances, some of the facies can be detected using Landsat MSS and TM if data can be acquired at the end of the melt season (Williams, 1987; Hall et al., 1987). As the melt season progresses, snow and firn melt from the lower elevation parts of a glacier and expose bare glacier ice. Since ice has a considerably lower reflectance than does snow and firn, especially if the ice is dirty, reflectance zones may be delineated for the Grossglockner glacier system. Results have shown that factors such as fresh snow and desert dust can obliterate the surficial expression of the glacier facies (Hall et al., 1987).

Other work has shown that the Landsat TM digital numbers (DNs) can be converted to realistic reflectance values that compare favorably with measurements acquired in-situ (Hall et al., in press). With the ability to compute reflectance in individual Landsat bands, albedo, or spectrally integrated reflectance of snow, can be calculated (Dozier, 1984; Brest and Goward, 1987). However, data saturation in the first three Landsat bands can preclude the determination of albedo using Landsat data.

The Grossglockner is the highest mountain in the Hohe Tauern Range and is located in the eastern Alps of Austria. The Grossglockner peak is at an elevation of 3798 m. The Pasterze is the longest glacier of the Grossglockner glacier system, at 9.2 km. At the terminus, the glacier occupies an area which is 400 m wide. The Pasterze has four hanging glaciers to the southwest which contribute to a large lateral moraine. The Grossglockner glacier region is accessible by road except during the winter months.

The meteorological station, Rudolfshuette (2304 m) has collected data throughout the year since 1981 and is located approximately 5 km to the west of the uppermost part of the Pasterze. Since the Pasterze is located in the valley east of the Rudolfshuette, the data should be used with caution. However, the data show trends and give a clear picture of the climatic conditions in this region of the Alps. The five year average temperature is -1.04 °C and the average precipitation is 2291 mm per year. The average annual snowfall is 1720 cm. The month with the deepest snow is March with an average snow depth of 239.6 cm (Zentralanstalt, 1987).

The Pasterze Glacier reached a maximum extent between the years 1620 and 1650, and again by 1856 and 1920 (Haslacher, 1983). Over the last 130 years the glacier recession has been recorded (Eckelt, 1967; Patzelt, 1980). Since 1965 the Pasterze lost 317 m (Kinzel, 1966; Patzelt, 1977). While the Pasterze Glacier continues to recede, some nearby, smaller glaciers have been advancing.

Approach

Two summer Landsat TM scenes of the Grossglockner glacier system have been acquired. Scene #50155-09272 was acquired on 03 August 1984 and scene #50891-09195 was acquired on 09 August 1986; the scenes were registered using an interactive image processing system on a VAX microcomputer. From the 1984 scene and analysis of topographic maps, the approximate boundary of the drainage basin of the Pasterze Glacier was delineated. Reflectances of the Pasterze Glacier were calculated using a formula which takes into account the solar zenith angle, the earth-sun distance and the exoatmospheric solar irradiance at the time of each Landsat overpass (Markham and Barker, 1986).

Because much of the terminus of Pasterze Glacier has a spectral reflectance that is similar to that of the surrounding terrain, it was difficult to measure the size of the entire glacier accurately. In order to improve our ability to distinguish the glacier from the surrounding area, the ratio of the DNs from TM band 4 to the DNs from TM band 5 was calculated. Subsequent analysis of the glacier was done using the band 4/5 ratio image.

Results

The area of the Pasterze Glacier basin was found to be approximately 18.5 km^2 as determined from TM digital data. This is thought to be an underestimate because part of the terminus is so debris-covered that it cannot be distinguished from the surrounding terrain. Figure 1 shows the 4/5 ratio image of the Pasterze Glacier in 1984 and 1986, respectively. The area of melting is obviously greater in 1986, with the bare glacier ice comprising 3.87 km^2 of the total area in 1984 and 6.46 km^2 in 1986, as calculated from the TM data. From the TM 4/5 ratio images, one can locate the seasonal snowline which delineates the area of most active melt in the lower part of the glacier.

Figure 1. TM band 4/5 ratio images of the Pasterize Glacier showing area of bare glacier ice.

The average reflectance of the Pasterze Glacier basin was calculated from the 1984 and 1986 TM scenes. Results show a marked decrease in average reflectance in 1986 as compared to 1984 in TM band 4 (0.76 - 0.90 μm) where only 5% and 7% of the pixels were saturated, respectively. The TM band 4 reflectance was 60.2% for 03 August 1984 and 52.2% for 09 August 1986. Saturation in TM bands 1-3 (0.45 - 0.69 μm) was so severe that average reflectance values are not meaningful and are therefore not reported. This decrease in reflectance is primarily due to the expanded area of melting in August of 1986 as compared to August of 1984.

Discussion and Conclusion

Retreat of glaciers can be measured quantitatively using Landsat TM data, by measuring a change in the position of the termini and also by measuring changes in the average reflectance of a glacier over a period of years. A marked change in reflectance is usually due to a change in the size of the area of melting. Thus, widespread melting of glaciers over key regions can be monitored and measured. This method of monitoring change in glacier mass balance is often limited to the use of TM band 4 because the pixels in TM bands 1-3 within the accumulation area may be saturated.

We have shown that the change in reflectance can be quite significant as a result of glacier retreat. Using a combination of MSS and TM data, changes in many of the world's glaciers over about a 16 year period may be measured. Such a study of the Grossglockner glacier system would be especially interesting because some nearby meteorological data are also available for comparison with the Landsat data.

In conclusion, we have found that 20.8% of the total area of the glacier consisted of bare ice in 1984 as compared to 34.7% in 1986. The TM band 4 reflectance was found to decrease from 60.2% in 1984 to 52.2% in 1986. The 1986 retreat is caused by less snowfall and higher air temperatures in 1986. If large-scale retreat of glaciers should occur, large-scale decreases in glacier reflectance are likely. This should permit greater absorption of solar radiation and may thus further enhance regional melting and glacier retreat.

References

Benson, C. S., 1962: Stratigraphic studies in the snow and firn of the Greenland Ice Sheet, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) Research Report No. 70.

Benson, C. S. and R. J. Motyka, 1979: Volcano-glacier interactions on Mt. Wrangell, Alaska, in Geophysical Institute Annual Report, 1977-78, University of Alaska, Fairbanks, AK.

Brest, C. L. and S. N. Goward, 1987: Deriving surface albedo measurements from narrow band satellite data. International Journal of Remote Sensing, V. 8, pp. 351-367.

Dozier, J., 1984: Snow reflectance from Landsat-4 Thematic Mapper. IEEE Transactions on Geoscience and Remote Sensing, V. GE-22, pp. 323-328.

Eckelt, H., (Ed), 1976: Kozenn Atlas, Verlag Ed Hoelzel, Vienna, p.22.

Hall, D. K., R. A. Bindschadler, J. P. Ormsby and H. Siddalingaiah, 1987: Characterization of snow and ice reflectance zones on glaciers using Landsat thematic mapper data. Annals of Glaciology, V. 9, pp. 104-108.

Hall, D.K., R. A. Bindschadler, J. L. Foster, A. T. C. Chang and H. Siddalingaiah, in press: Comparison of in-situ and satellite-derived reflectances of Forbindels Glacier, Greenland.

Haslacher, P., (Ed.), 1983: Gletscherweg Pasterze, Oesterreichischer Alpenverein, pp. 22-23.

Kinzel, H., 1966-1976: The Glaciers of the Austrian Alps, Oesterreichischer Alpenverein, Mitteilungen, V. 22-34.

Markham, B. L. and J. L. Barker, 1986: Landsat MSS and TM post-calibration dynamic ranges, exoatmospheric reflectances and at-satellite temperatures. EOSAT Technical Notes, No. 1, August, pp. 3-8.

Mayo, L. R. and D. C. Trabant, 1984: Observed and predicted effects of climate change on Wolverine Glacier, southern Alaska, in The potential effects of carbon-dioxide - induced climate changes in Alaska - Proceedings of a conference (ed. J. H. McBeath), School of Agriculture and Land Management, University of Alaska, Fairbanks, AK, pp. 114-123.

Meier, M. F., 1983: Snow and ice in a changing hydrological world, Hydrological Sciences Journal, V. 28, pp. 3-22.

Meier, M. F., 1984: Contribution of small glaciers to global sea level. Science, V. 226, pp. 1418-1421.

Ostrem, G., 1975: ERTS data in glaciology - an effort to monitor glacier mass balance from satellite imagery. Journal of Glaciology, V. 15, pp. 403-415.

Paterson, W. S. B., 1981: The Physics of Glaciers. 2nd Edition, Pergamon Press, 380 p.

Patzelt, G., 1977-1987: The Glaciers of the Austrian Alps, Oesterreichischer Alpenverein, Mitteilungen, V. 35-42.

Patzelt, G., 1980: The Austrian Glacier Inventory: Status and First Results, World Glacier Inventory: Proceedings of the Rieder Alp Workshop, September 1978, pp. 181-183.

Williams, R. S., Jr., 1987: Satellite remote sensing of Vatnajökull, Iceland. Annals of Glaciology, V. 9, pp. 127-135.

Zentralanstalt fuer Meteorologie und Geodynamik, Vienna, Computer Printout of Meteorological Data. Rudolfshuette, August 1983 - August 1987.