Introduction

Areas of perennially ice-covered land range in size from small patches of snow and ice, through mountain glaciers and icefields, to the great ice sheets of Greenland and Antarctica. If we were to consider our planet 20,000 years ago, we would also need to include the vast Laurentian ice sheet of North America (which covered Ithaca) and the Fennoscandian ice sheet of Eurasia. Glaciers and ice sheets sculpt the landscape, provide water for many communities around the world, attract mountain climbers and extreme skiers, but are in themselves very interesting objects of study. They respond to climate, and are thus a primary source of information about past and present climate change.

The change in climate from the last glacial episode to the modern inter-glacial period (the Holocene) represents one of the more drastic changes in the global environment. A more subtle change that is occurring in the most recent period of human history, a change whose future progression is the subject of much debate, is the warming of the planet during the past century (often referred to as "global warming"). Increasing evidence supports the idea that the warming is at least partially a result of increased concentrations of greenhouse gases in the atmosphere produced by the combination of the industrial revolution and the explosive growth of human population. Observations of the recession of mountain glaciers in many regions of the world is one of the primary lines of evidence for modern global warming. Water from melting glaciers adds to the volume of water in the oceans and produces much of the observed rise in sea level during the past century.

Field work on glaciers is difficult and challenging -- a glaciologist is often both scientist and a mountain climber (not a bad life!). Satellite remote sensing offers a new and very powerful way to study glaciers as well as many other features of Earth's surface. In this lab we will use satellite remote sensing to examine the Juneau Icefield and its many outlet glaciers. The icefield, located near the capital of Alaska, is part of a system of large icefields covering much of the near coastal mountain ranges of southeastern Alaska. We will see quite clear evidence for the diminution in the extent of glaciers during this century, as well as evidence for the much greater extent of glaciation during the last ice age.
Juneau icefield and its outlet glaciers. We first explore the nature of the satellite image and how computer image processing can greatly enhance our ability to view and analyze the image. We then identify various features of the glaciers, glacial erosion, and glacial sedimentation apparent on the satellite image. Certain of these features will permit you to estimate the velocity of ice flow in one of the glaciers. The second part of the lab will be done in the computer lab in Room 2161 Snee on your own using graphics material from the satellite images and from topographic maps of the region. The graphics material will be accessible with Arcview and will also be available in color on our WWW site and as black and white handouts.

Before the lab, you should read or re-read the chapter on glacier features in Skinner and Porter.

Satellite Remote Sensing

The images we will view were acquired by the Thematic Mapper (TM) sensor operating on the Landsat 5 satellite. We will look at two images, one on September 15, 1986, and the other on September 24, 1995. Both images were thus acquired near the end of the Summer melting (ablation) season for southeast Alaskan glaciers. As explained below, this permits us to determine the "equilibrium line altitude" for the glacier. The Landsat satellite flies in a "sun-synchronous" orbit, so that it takes images along each transit around 9 AM local time.

The TM instrument senses solar electromagnetic energy reflected from the surface in six bands of the electromagnetic spectrum: three bands in the visible and three bands in the near-infrared. The bands numbered 1, 2, 3, 4, 5, and 7 are centered about wavelengths as follows 0.48, 0.56, 0.66, 0.83, 1.65, and 2.22 micrometers (one millionth of a meter or one thousandth of a millimeter). The first three bands (1, 2 and 3) are in the visible part of the spectrum and bands 4, 5, and 7 are in the near infra-red part of the electromagnetic spectrum. With the computer, we can access any three of these bands, and feed them into the red, green, and blue guns of our color computer display. In this way we can make the infra-red data visible; the resulting computer display is called a "false color" image. The relative intensities of the chosen three bands can be manipulated by the computer ("enhanced") to give startlingly clear images of surface features. The image can be zoomed (or magnified) to see details of the scene, and you can even examine the pixel elements from which the picture is composed. The image can be mosaiced with other images to form views of huge areas (for example, see the mosaic of southeastern Alaska on the web site). The image can be explored by "roaming" or "panning" to view different parts of the image at whatever resolution is convenient.

The resolution of ground features in the image is limited by the aperture of the TM sensor and the distance between the satellite and the surface (for the Landsat satellites, about 705 kilometers). The resolution of TM images is about a 30 meter square on the ground. The TM "picture" is formed by pixel elements corresponding to squares of a checkerboard with 30 meter spacing on the ground. Each pixel contains a single measure of intensity for each of the six visible and near-infrared bands, corresponding to the intensity of the reflected energy averaged over the 30 by 30 meter patch of the earth's surface. A typical TM "scene" such as the one we will examine consists of a 185 by 185 km area below the track of the satellite, composed of about 6166 by 6166 pixels (over 38 million pixels).

The intensity measured by the TM sensor in each wavelength band is given by what is called in computer jargon a "byte integer" - i.e., an integer specified by only eight bits in the computer binary number system, which means only integers between 0 and 255. This number requires a calibration formula to calculate the actual intensity of the electromagnetic radiation in appropriate units as received by the satellite sensor. In our image this calibration has not been done, so we will deal simply with the byte integers.

For each pixel we have six bytes for six bands (one byte for each band), giving us a grand total of about 228 megabytes for a single scene. It is only in the past 15 years or so that computers available to university scientists have become both cheap and powerful enough to handle such enormous quantities of data.

We will first use our image processing program to examine the different bands, the utility of false coloring and enhancement, and explore the resolution of the image. Then we will proceed to examine the Juneau Icefield and some of its glaciers, and set you on your way to further analysis using images clipped from the satellite image that will be available for further inspection via a WWW browser. You will interpret and analyze the clips with the help of USGS maps with contoured elevations of the region.
The Juneau Icefields and glaciers

The icefields and glaciers of southeast Alaska, among the largest on earth outside of Greenland and Antarctica, are fed by abundant moisture coming in from the Pacific Ocean. The moist air masses are lifted upwards in flowing over the coastal mountains. The rising air cools and, as the dew point is reached, water vapor condenses and precipitates out as rain or snow. This produces intense levels of precipitation over the mountains. The precipitation falls mainly as snow during the cold northern winters. In areas where the accumulation of snow exceeds the melting over an annual seasonal cycle, the snow metamorphoses to ice as it is buried by successive annual layers, and eventually flows downhill (by plastic creep). As explained in the assigned reading in the textbook, the glaciers are "rivers" of ice flowing under the force of gravity from the areas of net accumulation at high elevations to areas of net loss at lower elevations. The extent of the glaciers is determined by this mass budget of ice. The Landsat images that we work with were both obtained on September, at the end of the melting season, just before the snows of Fall and Winter return to the region. We can see the extent of snow that accumulated during the previous Winter that was not completely melted over the Summer melt season, which thus outlines the area where net accumulation occurs.

Materials

The xeroxed figures enclosed with the lab show several views of the region of interest. They include the following:

- Fig. A. Thematic Mapper image (1986) of entire Juneau Icefield (the color version, Fig. A3 is viewable over the internet)
- Map 1: overview map of Alaska and British Columbia, for regional context.
- Map 3. USGS map of western part of Juneau Icefield, with contours of land elevations
- Map 4. Portion of USGS 1:63,360 scale map of the region of the Gilkey Glacier
- Figs. C, F. Thematic Mapper images (1986) of Gilkey glacier (color versions are viewable over the internet)
- Map 5. Portion of USGS 1:63,360 scale map of the Taku Glacier.

In lab, you will use Arcview to examine the two Landsat Thematic Images. In addition, Color images of clips from the Landsat Thematic Mapper image are accessible from this web site, and should be used in conjunction with the handouts. There are also some nice field photos.

Exercises

1. Glacier features.
   Identify the features listed below. You can use the maps or images (Figs. A-F) to help with the identifications, but locate the features on Map 3 by placing the letters given below in the appropriate position on the map:
   a. medial moraine
   b. terminal moraine
   c. glacier terminus
   d. trim line: evidence for recent glacier recession
   e. ice fall
   f. tributary glacier

2. Glacier Equilibrium Line Altitude.
   In class we will go over the enhancement of the images to bring out the "snowline" or "firn line". This is the boundary on the glacier taken at the end of the Summer melt season that separates
   • the higher and cooler elevations where last winter's snow has not completely melted (the zone of net accumulation or net mass gain taken over a year), from the
• the lower warmer elevations on the glacier where last winter’s snow has entirely melted and older snow and glacier ice are melting (the zone of net ablation or net mass loss taken over a year). If the snowline is determined in late summer or fall, just before the winter snows begin again, the snowline is a good estimate of that year’s “equilibrium line” on the glacier, the line where net mass gain and loss is zero. The text explains why such a line exists. The elevation of the equilibrium line is called the “equilibrium line altitude” or “ELA”. This is a sensitive indicator of yearly changes in the glacier mass balance caused by climate change. The satellite images used in this lab were both taken in September, a good time to see the equilibrium line in the SE Alaskan region.

In contrast, the position of the terminus - the lower elevation, down-stream end of the glacier - responds more slowly to these mass balance changes; the slow flow of glacier ice integrates the yearly effects of changes in mass balance over periods of decades or more. The larger the glacier the longer the integration time. If the mass balance is consistently negative (i.e. mass loss by melting or caving exceeds mass addition by snowfall) then the terminus will recede, while if the mass balance is consistently positive the terminus will advance.

On the images, the snowline is distinguished as a transition from • high reflectance snow in the near infra-red and visible bands (especially in band 4) of the previous winter’s still unmelted snow, to • the lower reflectance glacier ice.

We will show this in the class demo. The transitions are clearly visible on the black and white xeroxed images. 2a. You will use the topographic maps (Figs. 4-5) in conjunction with the images available in lab (and the color images on the web site) to estimate the elevation of the ELA’s on three glaciers at two times separated by nine years. You have to correlate features on the images with what is shown on the topographic maps in order to use the contour lines to determine the appropriate elevation.

Specifically, estimate the ELA’s on the following glaciers for both the 1986 and 1995 scenes:
• Taku Glacier
• Mendenhall Glacier

Use the handout-maps to help you locate these glaciers.

2b. What mean annual temperature do you think the ELA approximately corresponds to? Why?

2c. What do your results suggest regarding the change of mass balance and possible climate change over the nine-year period between 1986 and 1995?

3. Glacier Velocity and Ogives.

How fast are the glaciers moving? One way to estimate this is by measurements of the wavelength of wave-like features of the glacier surface topography called “ogives” (pronounced oh-jives). These are produced where the ice of the glacier moves over a particularly steep part of its path, so steep that the glacier forms an “ice fall”. The photos (Figs. G-J) on the web site show these quite clearly. The ice stretches and is often broken up while passing over the steep drop, thereby exposing more surface area to the effects of melting in the Summer and snow fall in the Winter. While traversing the ice fall the glacier therefore suffers more ablation in summer or more accumulation in winter, because in each case the exposed surface area is increased for a given length of time. Thus when the ice reforms at the base of the icefall and continues flowing along a more subdued downhill slope, it has ridges (winter on the icefall) and troughs (summer on the icefall) which then proceed to flow downstream with the rest of the glacier. The ogives are known to have this seasonal cycle and therefore record time: successive peaks (or troughs) represent one year of flow past the ice fall.
Question #3:

Since successive peaks or troughs represent one year of flow, then measurement of the peak-to-peak or trough-to-trough distance, say in meters, represents the velocity of ice flow in meters per year. To get a better estimate, measure the distance corresponding to a large but countable number of peaks and troughs. Use the scale on the topographic map provided to measure distance between points on the image that you can correlate with points on the map. In this way you can measure distance on the image. What, then, is the average annual flow velocity on the Gilkey Glacier for 1986? Assume that the glacier flows with the same velocity as that indicated by the ogives.

Question #4

Examine the large map of Glacier Bay National Park. Note that the historical positions of the major glaciers are given by gray lines within the bays.

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- Since 1780, how far have the glaciers in Glacier Bay retreated?
- What is the average annual rate of retreat?
- Look at some of the more recent terminus positions on the Muir Glacier, the Grand Pacific glacier, or the Johns Hopkins Glacier. Has glacial retreat remained constant? If not, how has it changed?

Question #5

Examination of the trim lines of glaciers on the Juneau Icefield show that these glaciers have been receding. Glaciers represent the storage of water on continents in the form of ice. When glaciers melt, the water is returned to the ocean. Consider the table of data below, and calculate the amount of sea level rise (in meters) that would occur if the following icefields were to melt away entirely (note—use a simple “bathtub” model for the ocean; a rectangular box with vertical walls):

- All ice fields and valley glaciers
- Greenland ice cap
- Antarctic ice cap

<table>
<thead>
<tr>
<th>GEOGRAPHIC REGION</th>
<th>AREA (KM²)</th>
<th>VOLUME (KM³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All ice fields and valley glaciers</td>
<td>500,000</td>
<td>240,000</td>
</tr>
<tr>
<td>Greenland</td>
<td>1,726,400</td>
<td>2,600,000</td>
</tr>
<tr>
<td>Antarctica</td>
<td>13,586,380</td>
<td>30,110,000</td>
</tr>
<tr>
<td>All Oceans</td>
<td>361,000,000</td>
<td>1,350,000,000</td>
</tr>
</tbody>
</table>

**Table 1: Estimated current area and volume of glaciers (Williams & Hall, 1993).**
Some useful WWW sites

Additional information is available at the following sites:

• See nice photos in the "virtual tour" of the Mendenhall Glacier.

• A really interesting and beautiful site on Alaskan glaciers not too far away from the area of interest in this lab: "A Multimedia History of Glacier Bay, Alaska".

• See Cornell's research on satellite glaciology in SE Alaska. For images of glaciers in the Patagonian region of southern South America, a region of huge icefields and glaciers comparable to southeast Alaska, go to our research site "Surface Properties, Topography and Motions of Patagonian Glaciers". Under "Glacier Velocity and Topography" you can find a link to ogives.

• Nick Short's tutorial, "Remote Sensing and Image Interpretation & Analysis", an excellent, accessible source of information.

• Latest information on the newest Landsat program, Landsat 7, with lots of information about the Landsat program in general.