Estimating Glacial Volume on the Tibetan Plateau:
A Combination Approach of Numerical Modeling and Remote Sensing

Introduction

The retreat of the Antarctic and Greenland ice sheets, as well as that of glaciers worldwide, is a major consequence of global warming (Folland 2002, Kulkarni 2007). Much of the world’s freshwater reserves are stored in these bodies of ice and snow (Gleick 1996); as they melt at unprecedented rates, worldwide average sea level is on the rise, glacial lakes burst and flood mountain valleys, and changes in total snow cover affect global albedo (ICPP 2010, U.S. Global Change Research Program 2010, Carrion 2010). The glaciers of the Tibetan Plateau are an important water source for the most densely populated region on Earth (Institute of Tibetan Plateau Research 2010). The melt water of these natural, frozen reservoirs enters the channel heads of the region’s high-flow rivers, such as India’s Brahmaputra, the Indus River and the Ganges; China’s Yellow River and the Yangtze; and Southeast Asia’s Mekong. These rivers provide for the freshwater needs of over half a billion people (Cruz 2007, Kehrwald 2008). As the population of this region grows, the demand for water is increasing. Due to an increase in average temperatures at high elevation over the last 50 years, the vast majority of the glaciers on the Tibetan Plateau are receding and these reservoirs are shrinking (Bolch 2006, Yao 2003 & 2007).

In an effort to prepare for future water demand, scientists have mapped the glaciers on the Tibetan Plateau using satellite imagery and have then calculated the amount of freshwater that is held in the ice and snow of these glaciers; this is called snow water equivalent (SWE) (Dyurgerov 2005, Kulkarni 2007, Kehrwald 2008). The snow water equivalent of the Tibetan Plateau’s glaciers, a significant part of the region’s future water supply, has been calculated and modeled based on estimates of glacial area and volume. However, these estimates have not accounted for mass loss through high-elevation thinning (Kehrwald 2008). Because measuring glacial depth by drilling ice cores is difficult and expensive, most estimates of glacial volume employ a simple equation to proximate glacial depth (Yao 2003, Kulkarni 2007, Inman 2010). However, these calculations have been determined to have up to 20 percent error and do not accurately reflect the mass wasting that is occurring on many of the glaciers on the Tibetan Plateau (Kulkarni 2007). Ice cores collected from several high-elevation glaciers in 2006 indicate that glaciers are thinning, losing volume, as they lose area (Kehrwald 2008). Volume is an important component in the hydrological modeling that determines the glaciers' SWE. Failure to accurately estimate the SWE of these glaciers due to incorrect volume inputs leads to faulty predictions of future freshwater availability. If the glaciers of the Tibetan Plateau recede faster than expected, then there could be serious water shortages for significant portions of the region's population. These shortages would affect agriculture and thus food and water security; they would also threaten the ability to produce electricity in the region's hydroelectric power plants (Madan 2005).

I propose a combination approach of numerical modeling and remote sensing to better estimate total glacial depth and volume. Separately, each method has its weaknesses. Remote sensing provides data about glacial conditions and areal extent but is unable to determine glacial depth. Numerical modeling through the mass balance equation can estimate changes in glacial volume, but it is dependent on external inputs in order to provide accurate information. So when implemented in concert, the two methods make up for the other's weaknesses and can provide accurate estimations of glacial volume. Better estimates of glacier volume will improve the understanding of the effect of climate change on glaciers and help to more accurately predict future water availability in the regions surrounding the Tibetan Plateau. This will give regional planners the information they need to prepare water conservation efforts or flood control as the case may be.

Background

The Tibetan Plateau is located in Central Asia, straddling southwestern China and northern India (see Fig. 1). The plateau's high elevation and geographical location have made it home to some of the world's largest and highest glaciers, earning it the nickname the "Tibet Third Pole." The Royal Meteorological Society "claims that the Tibetan Plateau is one of the most sensitive areas in the world to climate change; consensus now holds that its mean annual temperature has increased by 0.3° C per decade over the last fifty years" (Carrion 2010). The glaciers in the Himalayas and Tibet cover more than 35,000 km^2 (Dyurgerov 2005). Outside of the polar ice caps, this region holds the world's largest reserves of freshwater (Gleick 1996, Kaser 2006). The glaciers of the plateau contribute up to 70 percent of the water in some of the Asian continent's largest rivers (Kehrwald 2008). Glaciers are not static features; over the course of a year, a glacier can retreat (shrink), advance (grow), or remain stable. Glaciers are particularly sensitive to climactic change, retreating or advancing depending on specific environmental variables. Increased glacial melting directly impacts the region's hydrologic cycle, the volume of river discharge, and there is concern about the sustainability of the water supply (Barnett 2005).

Researching the glaciers of the Tibetan Plateau is important for many reasons. More information about the annual changes in glacial mass will help researchers understand the relationship between aspects of climate change and glacier retreat. Better estimations of glacial volume will provide more accurate information to regional planners about future water availability and thus impact billions of lives. Knowledge and experience gained from mass balance modeling and new remote sensing techniques can be applied to other mountains and glaciers.

Figure 1. The Tibetan Plateau, major river systems, and the surrounding regions (Schneider 2008).

The History of Measuring Glaciers

The first studies of glacial mass were conducted under the direction of the Commission on Glaciers on the Rhône Glacier in the Swiss Alps during 1874-1908 (Dyurgerov 2002). Initially, these studies of glacial mass simply focused on growth and retreat, which was roughly measured by the change in glacier terminus. This method was problematic because the exact terminus is difficult to define. Annual snow accumulation and ablation on the glacier change the shape of the terminus and “these measurements were complicated by measuring to different locations year-to-year of an irregular terminus” (Fountain 1997, Granshaw 2007). Terminus position also fails to account for glacial thinning on the snow’s surface.

Aside from measuring the changing terminus, ablation stakes can be used to measure changes in mass balance by measuring the rise or fall of the glacier’s surface. These stakes are distributed across the glacier at the height of snow accumulation in the spring and measured. The stakes are measured again in the fall after most of the snowpack has melted. “The sum of the two (winter gain and summer loss) is the mass change of balance of the glacier” (Granshaw 2007). Ablation stakes are somewhat accurate in showing the differences in snow distribution as the surface changes throughout the season; however, this method is subject to error due to the effects of wind scour and subsurface melting (Marks 1992). This method is also labor intensive, requiring at least two trips to the glacier for installation and measuring every year. This is not feasible for the majority of the glaciers on the Tibetan Plateau.

There have been many efforts to calculate glacier depth and volume by deriving equations based on sample field observations. One such equation used for glaciers in the Himalayas is presented by Kulkarni:

$$H = -11.32 + 53.21\, F^{0.3},$$

where H is glacial depth (m) and F is glacial area (sq. km) (Kulkarni 2007). Glaciologists are able to determine the areal extent (F) of these glaciers through satellite imagery or from field surveys. The advantage of equations like this one is that once areal extent has been determined it is relatively simple to calculate depth and then volume. However, the constants in this equation were derived from sample field observations, and these numbers are biased because they depend on measurements taken only from easily accessible sites and fail to include large groups of glaciers. Thus, they are not representative. Additionally, ice cores collected from several high-elevation glaciers in 2006 by Kehrwald et al. indicate that glaciers are thinning, losing volume, as they lose area. Analysis of the ice cores revealed that the extent of glacial thinning was greater than estimated and that mass wasting on glacier surfaces is having a significant impact on glacial volume. A different method for estimating glacial depth is needed to correct for the error inherent in this simplistic approach.

The advent of remote sensing has allowed glaciologists to study many glacier characteristics, and the applications of this technology continue to be tested and pushed to new limits. However, there is not yet a remote sensing instrument that is capable of directly measuring glacial depth. Researchers, such as Kelly et al., have developed algorithms to estimate snow depth, but these equations depend on location specific data about reflectance values for specific depths and densities (2003). This kind of information is generally unavailable for the majority of the glaciers on the Tibetan Plateau. There are also difficulties associated with the aspect, slope and size of these glaciers. The angle of the mountains on the Tibetan Plateau makes it difficult for overhead instruments to obtain accurate scans, and the coarse resolution of many of the current instruments limits the value of any data collected (Che 2003).

On another front in the remote sensing of snow and ice, there have been promising developments with the recent launch of both the Gravity Recovery and Climate Experiment (GRACE), “which detects subtle changes in the Earth’s gravity field caused by on-the-ground variations in water, ice or plant life,” and the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) (Inman 2010). However, a study of GRACE data on glaciers in the Himalayas recognizes that its ice mass loss estimates may be significantly skewed by intensive groundwater pumping in India’s nearby agricultural lands (Matsuo 2010). AMSR-E, while useful in collecting data on the polar ice caps, lacks the fine level of resolution needed to analyze small, inclined glaciers. Directly measuring glacial depth and volume from space-born instruments is wrought with complex challenges, is subject to significant error, and is still being developed.

This research will expand on previous work by combining several measuring techniques in order to more accurately estimate glacial depth and volume. The combination approach to estimating glacial volume that is proposed in this prospectus has not been used before because only recently have remote sensing instruments become refined enough to collect data on the key variables needed for glacier mass balance equations.

Understanding Glacial Net Mass Balance

The proposed method of estimating glacial volume hinges on an understanding of the variables that contribute to net mass balance, the results of net mass balance change, and the feedback loop that, in turn, influences the initial contributing variables. Mass balance refers to the balance in a glacier between inputs (snow accumulation) and outputs (melting and ablation). A glacier is growing if the balance is positive and shrinking if it is negative (Lawrence 2002). Mass balance is usually referred to as a total loss or gain in glacier mass at the end of the hydrological year (Fountain 1997, Dyurgerov 2005). Figure 2 shows the relationships between the meteorological environment and net mass balance, the net mass balance and stream flow, and the change in glacial geometry and the meteorological environment. The complexity inherent in each of these steps makes it difficult to accurately predict or estimate empirical changes in the process. By isolating the constants and by finding ways to measure and calculate the variables, estimations of glacial volume can be improved.

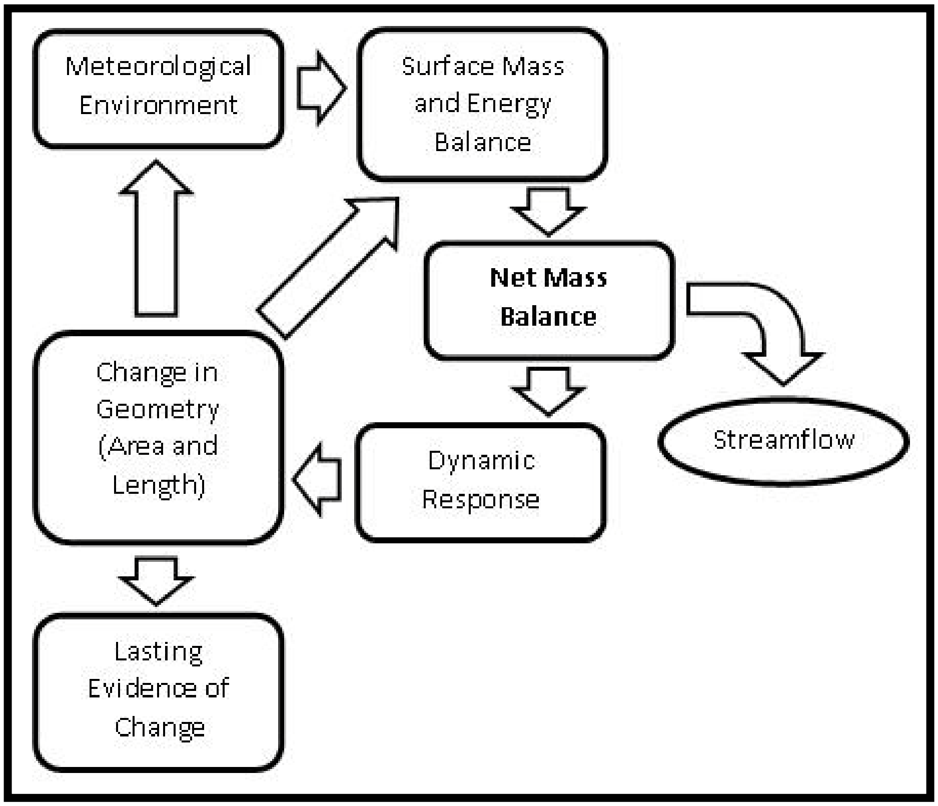

Figure 2. Processes that link meteorology with glacier mass balance and their effect on landscape (modified from Meier 1965 and Fountain 1997).

Equations for Calculating Glacial Net Mass Balance

Changing glacial mass can modeled through a mass balance equation. One method of calculating mass balance, the Energy-Exchange processes model, looks at all the variables in the system, such as net solar radiation, the turbulent exchange of sensible and latent heat from the atmosphere, the amount of precipitation, and heat exchange with the ground (Marks 1992). Because it specifically measures the transfers of energy, it is also known as the energy balance model. The Energy-Exchange processes model:

$$\Delta S = K + L + H + LE + R + G$$

where ΔS is heat storage change, K is shortwave (solar) radiation input, L is longwave radiation exchange, H is turbulent exchange of sensible heat with the atmosphere, LE is turbulent exchange of latent heat with the atmosphere, R is heat input by rain, and G is conductive exchange of sensible heat with the ground (see Fig. 3). The energy balance approach, Energy-Exchange processes model, is a difficult way to estimate heat storage change because it requires inputs for many different types of variables. Also, it can be expensive, and it is “virtually impossible to collect such data at enough locations to be spatially representative of even a moderate-sized watershed” (Lawrence 2002).

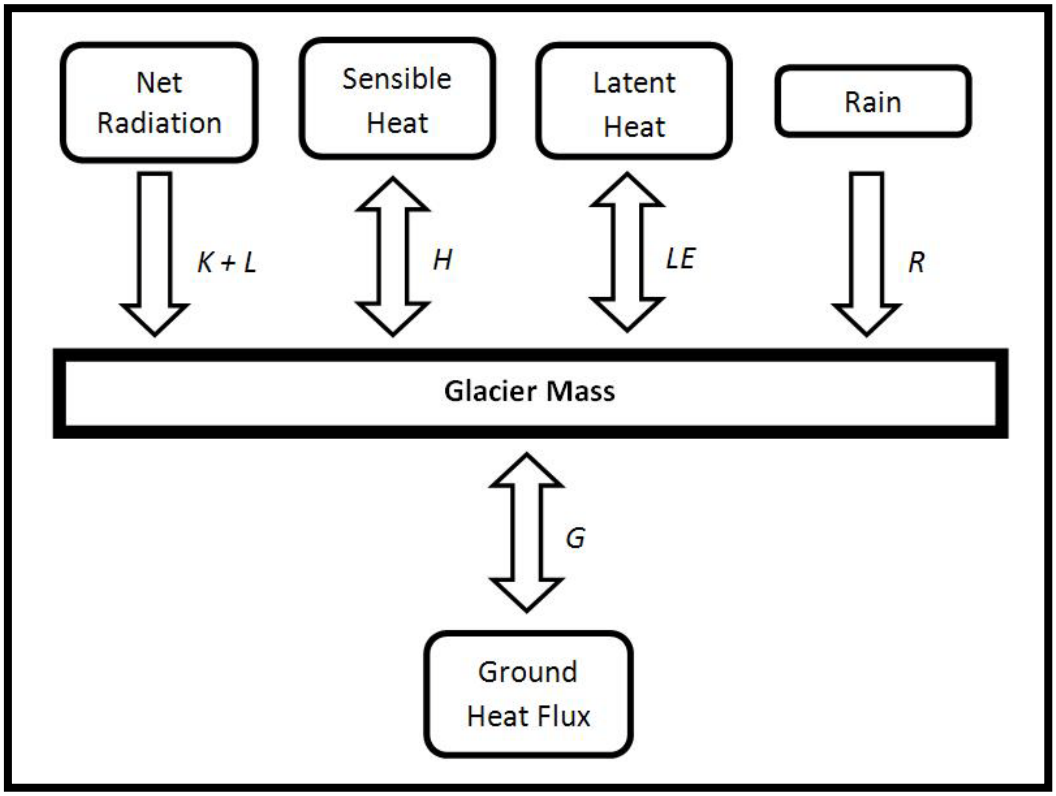

Figure 3. Energy-Exchange processes model (modified from Carrion 2010).

The Temperature-Index approach is an alternative to the complex Energy-Exchange processes model. This approach is based on several assumptions about the relationships between variables such as solar radiation and air temperature or the linear behavior of melting snow. “During melting, the snow-surface temperature is at or near 0° C, that energy inputs from longwave radiation and turbulent exchange are approximately linear functions of air temperature, and that there is a general correlation between solar radiation and air temperature” (Lawrence 2002). The Temperature-Index approach:

$$\Delta w = M \cdot (T_a - T_m), \quad T_a >= T_m$$

$$\Delta w = 0, \quad T_a < T_m$$

where Δw is snowmelt, M is the melt coefficient, T_m is the snow temperature, T_a is the air temperature (see Fig. 4). If T_a is greater than 0° C, there will be some degree of snowmelt. If T_a is less than 0° C, then there will be no snowmelt. Despite its simplicity, the Temperature-Index model has proven to be a powerful tool for melt modeling; often “on a catchment scale” outperforming Energy-Exchanges models. The simplicity of the Temperature-Index approach over the Energy-Exchanges processes makes it the model of choice when estimating glacial mass balance.

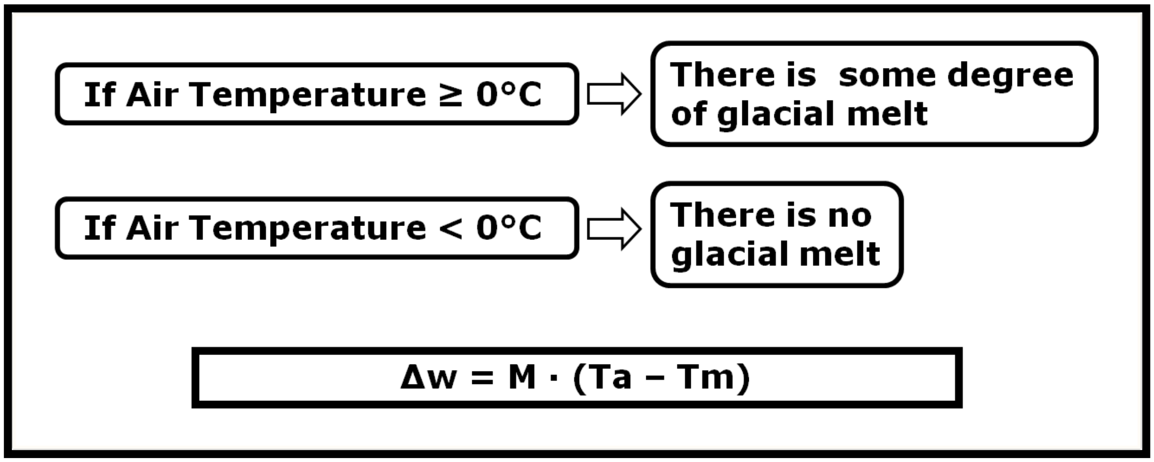

Figure 4. Temperature-Index approach and its outputs (adapted from Lawrence 2002).

The methods of studying and measuring glaciers have come a long way from the initial Rhône Glacier survey conducted in 1876 in the Swiss Alps. Increased understanding of the hydrological cycle, research on the changes of mass balance in the cryosphere, and advances in technology have improved the ability to measure important glacier characteristics. Combining the best of these methods and techniques in a way that highlights their strengths and minimizes their weaknesses will allow researchers to calculate, with better accuracy, glacial mass and estimate, quantitatively, changes in glacial volume.

Methodology

Due to their remote locations and environmental hazards, the glaciers of the Tibetan Plateau have, for the most part, not been adequately mapped, and their mass balances have been poorly sampled (Berthier 2006, Inman 2010). This lack of specific data has hindered efforts to accurately estimate the volume of these glaciers. Inaccurate estimations of volume translate into inaccurate SWE estimations and also obscure the impact of climate change on the glaciers. Better estimations of glacier depth will make both volume and SWE calculations more accurate and improve the data available for water resource management.

This article proposes combining several existing glacier measuring techniques and methods in a new way that would improve the accuracy of glacial volume estimations. Figure 5 shows the process of this proposed methodology. Combining the numerical modeling and remote sensing approaches to measuring glaciers reduces the error of glacial volume estimation by:

1. Determining the areal extent of specific glaciers with satellite imagery.
2. Measuring the glacier's depths through ice coring or ground penetrating radar.
3. Establishing baseline volumes for the glaciers.
4. Incorporating remotely sensed data for these glaciers into mass balance equations to estimate future changes in volume.
5. Verifying the validity of the model through ground truthing.

This method of calculating glacial area, depth, and volume is more accurate because it becomes site specific and takes into account rapidly changing environmental factors that significantly alter glacial mass.

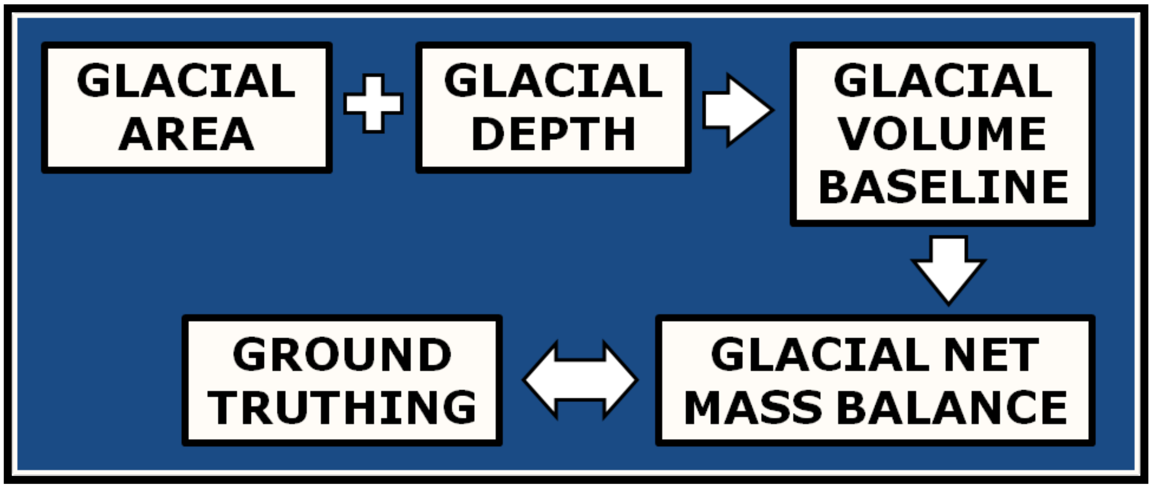

Figure 5. A combination approach of numerical modeling and remote sensing to determine changes in glacier volume.

Glacial Area

Satellite imagery is an invaluable tool in determining the areal extent of glaciers. Remote sensing instruments are capable of mapping ground features from space. The Landsat satellite program provides multispectral Thematic Mapping (TM) data at a resolution of 30 meters. A TM4/TM5 ratio image can be created from this Landsat data and then used to delineate glaciers (Bloch 2006). Misclassified pixels of vegetated areas and lakes can be eliminated by using the Normalized Difference Vegetation Index (NDVI). Another remote sensing instrument aboard the Terra EOS satellite, the Advanced Spaceborne Thermal Emission and Reflection Radiometer / Shuttle Radar Topographic Mission (ASTER/SRTM), produces digital elevation models (DEMs) that are also suitable for mapping glacial extent (Berthier 2006). The TM images and DEMs are both created as raster files. So the process goes from remote sensing instruments to satellite imagery to glacier boundary delineation; this produces an accurate estimation of glacial area.

Glacial Depth

Although there is great potential in remote sensing, the most accurate measurements of glacial depth are still collected in the field, on the surface of the glacier itself. There are two standard methods for collecting glacial depth data in the field. The first is a process of drilling through the glacier down to the bedrock below; this is called ice core drilling, or ice coring. Ice coring is able to provide exact depth measurements. When the drilling points are spatially distributed in a manner that represents the glacier's surface, then the depth data points can be interpolated. These interpolated points in conjunction with area and surface height create a realistic picture of the distribution of glacial mass in three dimensions.

While ice core drilling can provide highly accurate volume estimations, it requires trips to the glaciers and the accompanying difficulties, expenses, and time. The second, and more common, method is a complete survey of the glacier surface with ground penetrating radar (GPR). Ice thickness can be measured through GRP profiling. The survey is conducted by profiling along the central line and across the glacier at regular elevation intervals (Gergan 1999). GPR glacier profiling provides high resolution data that not only shows the distribution of glacial mass but also shows the locations and extent of exposed and hidden crevasses, subglacial lodgment till, subglacial pools, and the bedrock material. As with ice core drilling, GPR profiling is resource intensive; however, it offers high resolution data. Both methods, ice core drilling and GPR profiling, can be used to generate the highly accurate data needed to create a glacial volume baseline.

Glacial Volume Baseline

After measuring the areal extent and depth of a glacier a glacial volume baseline can be established. The TM and DEM rasters that contain glacier boundary data are combined with the specific depth measurements collected by ice coring or DPR. The ESRI ArcMap raster calculator can add these two data sets together and create a three dimensional data set that represents the glacier’s volume at the time it was measured. This calculated volume becomes the glacier’s baseline volume. This baseline can then serve as the basis for measuring annual change in the mass balance, as determined by a numerical modeling approach.

Glacial Net Mass Balance

After establishing a baseline glacial volume changes in glacial net mass balance can be estimated annually by numerical modeling. Remote sensing instruments can provide the data needed to run the mass balance models. This article proposes using the Temperature-Index model to estimate changes in mass balance because all the variable data needed for this model can be collected through remote sensing instruments and it performs as well as, if not better than, the Energy-Exchanges approach. Air and snow surface temperatures are key variables in the Temperature-Index model. The Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR) are two remote sensing instruments that create products with temperature data. MODIS produces both atmosphere data products and cryosphere data products at spatial resolutions of up to 250 meters and at temporal resolutions of about 48 hours. High quality spatial and temporal resolution is important in numerical modeling, especially in the difficult terrain of the Tibetan Plateau. The variables needed to calculate the melt coefficient can also be obtained from satellites. Albedo is detected by Landsat TM, and the slope factor can be drawn from the topography recorded in the ASTER DEMs. With all of this data combined in the Temperature-Index approach model, researchers can estimate the changes in glacier mass. That estimated change in glacier mass can then be subtracted from the initial baseline data.

The weakness of the Temperature-Index model is its inability to estimate gains in glacial mass. In order to overcome this shortcoming, SPOT-5 sensor data can be employed to measure snow accumulation on the glacier’s surface. This remote sensing instrument has high resolution data products that are suitable for the glaciers of the Tibetan Plateau. The HRS instrument on this satellite points forward and backward of the satellite; thus, it is able to take stereopair images almost simultaneously to map relief. The data collected from these instruments, rasters called digital terrain models (DTMs), measure topography and can be used with the baseline information to calculate changes in glacial surface height and volume.

At the end of each hydrological year, the total snow and ice accumulation due to precipitation is added to the baseline glacial volume. Then the reduction in glacial mass, as calculated by Temperature-Index model, is subtracted from the sum of annual accumulation and glacial volume. The resulting value is the current volume of the glacier. If the amount of snow and ice accumulation is greater, then the melt then the glacier is advancing. If the amount of snow and ice accumulation is less, then the melt, then the glacier is receding. Employing these methods would, in theory, mean that data collection in the field would only be necessary once for each glacier; future glacial volume estimates could be made by applying the mass balance model outputs to the original baseline.

Ground Truthing

The last part of the process is verifying the validity of the purposed method through occasional ground truthing. Ground truthing, in this case, is simply the process of checking the accuracy this proposed method of estimating glacial volume and changes in mass balance. This method’s accuracy can be evaluated in two ways: by comparing it with other methods of estimation and by comparing it with later field measurements. In order to objectively compare the different methods, a single glacier needs to be selected. The selected glacier must satisfy these conditions:

- It must be located on the Tibetan Plateau.

- It must be accessible and available for sampling (GPR profiling and ice core drilling).
- It must have up-to-date remote sensing data available.
- It must be a significant glacier in terms of size, melt water runoff, and contribution to a major river.

After the selected glacier is sampled and a baseline has been established, the first comparison could be made. After a year, remote sensing data is collected for the glacier, values for the Temperature-Index approach are entered into the model, and the resulting mass balance is added to the baseline. From that point comparisons could be made. The glacial extent as delineated from satellite images could be overlaid with glacial extent as measured in the field and a percent error could be calculated. If the researchers desire, another round of ice core sampling or GRP profiling could be done to establish a current baseline, a standard to measure the proposed method against alternative methods. Ground truthing could also include measuring the amount of glacial melt to check the Temperature-Index model. The data gathered from ground truthing can be compared with the modeling results, error can be calculated, and adjustments can be made to improve the model's estimations of glacial volume. The resulting percent error or deviation from the baseline would indicate which method was the most accurate.

Ground truthing provides assurance that the other components of the proposed method are providing accurate data and that the data is being synthesized in a manner that produces the most accurate estimations of glacial mass and volume as possible. While none of these components of measuring or modeling is new to the field of glaciology, the proposed combination of these techniques is original to this research. Baseline field data and net mass balance models working in concert with information provided by remote sensing instruments can better estimate changes in the volume of glaciers on the Tibetan Plateau.

Conclusion

This research proposes a new method of estimating glacial depth and volume through a combination approach of numerical modeling with the Temperature-Index Approach and remote sensing to determine areal extent and to provide data for modeling variables. This proposed method will improve the accuracy of glacial volume estimations. Accurate glacial volume estimations are important because they help measure the rate of glacier advance and retreat and also provide better estimates of SWE for use in water management planning. Failure to accurately estimate the SWE of these glaciers, due to incorrect volume inputs, leads to inaccurate predictions of future freshwater availability. If the glaciers of the Tibetan Plateau recede faster than expected, then there could be serious water shortages for significant portions of the region’s population.