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Quantification of glacier melt volume in the Indus River watershed

Maria Nicole Asay
Brigham Young University - Provo

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Maria Nicole Asay

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Summer B. Rupper, chair
Jani Radebaugh
Alan Mayo

Department of Geological Sciences

Brigham Young University

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ABSTRACT

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Maria N. Asay
Department of Geological Sciences, BYU
Master of Science

Quantifying the contribution of glaciers to water resources is particularly important in locations where glaciers may provide a large percentage of total river discharge. In some remote locations, direct field measurements of melt rates are difficult to acquire, so alternate approaches are needed. Positive degree-day modeling (PDD) of glacier melt is a valuable tool to making first order approximations of the volume of melt coming from glaciers. In this study, a PDD-melt model is applied to glaciers in the Indus River watershed located in Afghanistan, China, India, and Pakistan. Here, millions of people rely on the water from the Indus River, which previous work suggests may be heavily dependent on glacier melt from high mountain regions in the northern part of the watershed. In this region, the PDD melt model calculates the range of melt volumes from more than 45,000 km^2 of glaciated area. It relies on a limited suite of input variables for glaciers in the region: elevation, temperature, temperature lapse rate, melt factor, and surface area. Three global gridded climate datasets were used to determine the bounds of temperature at each glacier: UEA CRU CL 2.0, UEA CRU TS 2.1, and NCEP/NCAR 40 year reanalysis. The PDD melt model was run using four different melt scenarios: mean, minimum, maximum, and randomized. These scenarios account for differences in melt volume not captured by temperature, and take uncertainties in all input parameters into account to bound the possible melt volume. The spread in total melt volume from the model scenarios ranges between 27 km^3 and 439 km^3. While the difference in these calculations is large, it is highly likely the real value falls within this range. Importantly, even the smallest model volume output is a significant melt water value. This suggests that even when forcing the absolute smallest volume of melt, the glacier contribution to the Indus watershed is significant.

In addition to providing information about melt volume, this model helps to highlight glaciers with the greatest contribution to total melt. Despite differences in the individual climate models, the spatial pattern in glacier melt is similar, with glaciers contributing the majority of total melt volume occurring in similar geographic regions regardless of which temperature dataset is used. For regions where glacier areas are reasonably well-constrained, contributions from individual glaciers can be quantified. Importantly, less than 5% of glaciers contribute at least 70% of the total melt volume in the watershed. The majority of these glaciers are in Pakistan, the region with the largest percentage of known glaciers with large surface areas at lower elevations.

In addition to calculating current melt volumes over large glaciated areas, this model can also be used to determine future melt rates under differing climate scenarios. By applying suggested future regional temperature change to the temperature data, the impact on average melt rate over the watershed was found to increase from 3.02 m/year to 4.69 m/year with up to 2 °C temperature increase. Assuming glacier area remains relatively constant over short time periods, this would amount to a 145 km^3 increase in melt volume.

Keywords: Indus River watershed, glacier melt, PDD, Himalaya, climate change

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1. INTRODUCTION

Water resources are becoming increasingly important as world populations grow. In many locations glaciers are a significant proportion of these resources. As such, the ability to quantify glacier melt rate and volume contribution to a given watershed is particularly important. Unfortunately, the financial and scientific resources are not always available to do detailed hydrologic and glaciologic studies over large, remote regions. Determining the location and quantifying the significance of glacier melt remotely can be invaluable in such circumstances. To aid in the process of quantifying glacier melt without on-site information, this study has two aims. First, I developed an approach to calculate glacier melt from a variety of data sources and quantified the uncertainties that accompany such an approach. Second, the method was applied to the Indus watershed, a region where prior work suggests glacier melt may be a significant proportion of water resources in the region but limited on-the-ground studies have been completed (Immerzeel *et al*., 2010). In particular, this study makes first order calculations of the volume of glacier melt from more than 45,000 km^2 of glaciated area in the Indus River watershed both presently and in the future. This was accomplished by utilizing data from climate reanalyses, global climate models, and published data on glacier size and location. Through this approach, smaller regions of significant glacier melt volume and ultimately water resources within the Indus watershed have been determined. This will help scientists better focus future research on the impact of glacier and climate change on water resources in the Himalaya.

2. BACKGROUND

2.1 Climate Change and its Effect on Glaciers

Glaciers across the globe are changing in size, largely as a result of recent climate shifts (Jianchu *et al.*, 2007). While there are some anomalous regions where glaciers are increasing in size, globally glaciers are predominantly experiencing mass loss (Dyurgerov and Meier, 2005). Glaciers act as freshwater storage systems, and changes in their storage capacity have the potential to affect downstream river flow and sediment discharge, which in turn alter water resources for hydroelectric power and irrigation. The global implications of climate change on temperature have been reported by many groups including the International Panel on Climate Change (IPCC), but specific regional implications of this change need to be addressed in more detail (including Cruz *et al.,* 2007; Hasnain, 2002; Shrestha, 2004). In some areas, such as the European Alps, extensive research has been done to determine changes in glacial extent in response to changes in climate and its effect on the local environment. Methods of doing so have involved ice thickness and elevation distribution, decades of temperature data overlapping with early glacier monitoring, and remote sensing techniques (e.g. Farinotti *et al*., 2009; Huss *et al*., 2008).

By comparison, glaciers in many other parts of the world are less accessible and have been studied over much shorter time periods, if at all. This is especially true of the thousands of glaciers that cover the mountainous areas throughout Asia. The Himalayas constitute one of the largest glaciated areas outside of the polar icecaps (Dyurgerov and Meier, 2005) and lay in one of the most populated regions of the world (Immerzeel *et al*., 2010). Hence, changes in this region are of particular concern. Regional hydrologic studies suggest decreases in snow and glacier melt over the next several decades could be detrimental to populations in the Indus and Brahmaputra watersheds as temperatures rise and glaciers decrease in size because of the significant role this melt plays in regional water resources (Immerzeel *et al.*, 2010). Quantifying the changes in glacier melt today and in the future from individual glaciers and the region as a whole will provide further insight into the importance of the glaciers to water resources.

2.2 Numerical Modeling of Glaciers

Numerical modeling can be extremely beneficial in quantifying melt from glaciers. Several different numerical models have been employed to better understand how glaciers are responding to local and regional climate forcings. Three of the most common methods include using energy balance models, mass balance models, and positive degree day melt models. While each has strengths and weaknesses, they all have a place in better understanding glacier changes in the past and the future.

2.2.1 Energy Balance Models

One method for capturing changes in glaciers is to use an energy balance model. This requires measurements of detailed atmospheric data and glacier surface properties to calculate the energy inputs and outputs of a glacier system to quantify the mass loss in the form of melt and sublimation (Arnold *et al.*, 1996; Kayastha, 2001). For this method, scientists use weather stations on location at a glacier or remote data interpolated to glaciers of interest to measure variables such as air temperature above the glacier surface, incoming shortwave radiation, relative humidity, wind direction and speed, and precipitation (Arnold *et al.*, 1996; Kayastha, 2001). These variables are ideally measured multiple times a day over an extended period to account for changes over hourly, daily, and monthly timelines. The process is time consuming and requires considerable data to calculate changes in the glacier's mass balance, which is integrated to determine volume changes. Therefore, it is most effective in areas where long term and extensive research has been completed or is ongoing (Arnold *et al.*, 1996; Kayastha, 2001).

The detailed input in the model yields relatively high-spatial-resolution information about the glacier melt (Arnold *et al*., 1996). Overall, this type of approach requires a significant number of model inputs that can be difficult to acquire or downscale to a small region, and it is therefore challenging to apply to many remote locations.

2.2.2 Mass Balance Models

Mass balance models take a different approach than energy balance models. Scientists require measurements of the physical inputs, like precipitation, and outputs, including melt and sublimation, of the glacier system to understand how a glacier's mass will change with time (Johannesson *et al*., 1989). The models rest on the premise that climate signals are seen in glaciers as mass balance perturbations over the entire glacier (Johannesson *et al*., 1989). Like energy balance models, mass balance models require significant time investments with a need for years of physical measurements at the glaciated site or sites. While some information regarding the mass balance of glaciers is available through organizations like the World Glacier Inventory (WGI), the amount of mass balance data on glaciers is limited, and only a few dozen mass balance observations are currently being undertaken worldwide (Kargel *et al*., 2005). The mass balance data availability is limited in general. As of 2009 there were 3,380 mass balance measurements collected around the world, and they included information from only 228 glaciers (Zemp *et al*., 2009). Like most energy balance models, this approach can be difficult to use over large, remote regions where input data is more scarce and finding information for glaciers over a large region is challenging.

2.2.3 Positive Degree Day Models

Positive degree day (PDD) models take a different approach than those described above. They assume any melting in snow or ice over a designated time period is proportional to the sum of temperatures in degrees Celsius greater than the melting point or the sum of all positive degrees over that time period (Braithwaite, 1995). Unlike energy balance and mass balance models, PDD models require less hands-on data from each glacier of interest. Instead of relying on multiple, long-term measurements taken on site at a glacier, this method uses temperature to approximate the energy inputs that would cause a glacier to melt (Hock, 1999). There are many climate and remote sense datasets available that provide climate information. Temperature is one of the more certain variables available through these datasets. This model type relies on the premise that temperature is a good proxy for mass loss on glaciers over long time periods (Oerlemans, 2005). This assumption does not always hold true for small spatial extents or short timespans (Hock, 1999). The method depends on a limited number of input variables to approximate the volume of glacier ablation over a large area. These variables include the surface area of the glaciers of interest, the temperature at the glacier surface, and a melt factor (Ambach and Kuhn, 1985; Braithwaite, 1995; Rupper *et al.*, 2009). Melt factors are values that indicate how much melt would be expected at a given location per degree greater than zero (Kayastha *et al.*, 2003).

This study applies the PDD approach to quantify glacier melt rate and melt volume for several reasons. First, the study area is large, so a mass balance approach would not be realistic. Second, there are not enough weather stations or climate models at the right scale to easily use an energy balance model. Last, the temperature information in reanalysis datasets and global climate models is one of the more certain outputs, is readily available from multiple sources, and allows uncertainties in the melt model to be quantified. Given the size of the area and the accuracy in temperature data, the PDD model should produce good results.

3. STUDY AREA

The PDD approach to estimating glacier melt was applied to the Indus River watershed (Figure 1). This region was chosen for several reasons. As mentioned, the Himalayas and surrounding mountain ranges constitute some of the largest glaciated regions outside the polar regions (Dyurgerov and Meier, 2005). Some estimates suggest glacial resources in the Himalayas alone are more than 110,000 km^2 from more than 18,000 glaciers (Dyurgerov and Meier, 2005; Qin, 2002). The major rivers these glaciers contribute to are the Indus, Brahmaputra, Yangtze, and Ganges, as well as hundreds of smaller tributaries.

More than 178 million people rely on the water provided by the Indus River for agriculture, industrial development, and hydropower generation (Jianchu *et al*., 2007). Sources suggest the average Indus River discharge is between 4,300 m^3/s and 5,533 m^3/s, but annually it could be as high as 207 km^3/yr (Bookhagen and Burbank, 2010; Economic Commission for Asia and the Far East, 1966; Jianchu et al., 2007). Much of the discharge of the Indus comes from seasonal melt from thousands of glaciers of the northwestern Himalayas (Immerzeel et al., 2010; NSIDC, 1999, updated 2009). These glaciers are sensitive to shifting climate, and increasing regional temperature and changing precipitation patterns have the potential to alter glacier melt runoff rates dramatically, particularly in the monsoon-influenced valleys on the southern side of the range (Immerzeel *et al.*, 2010).

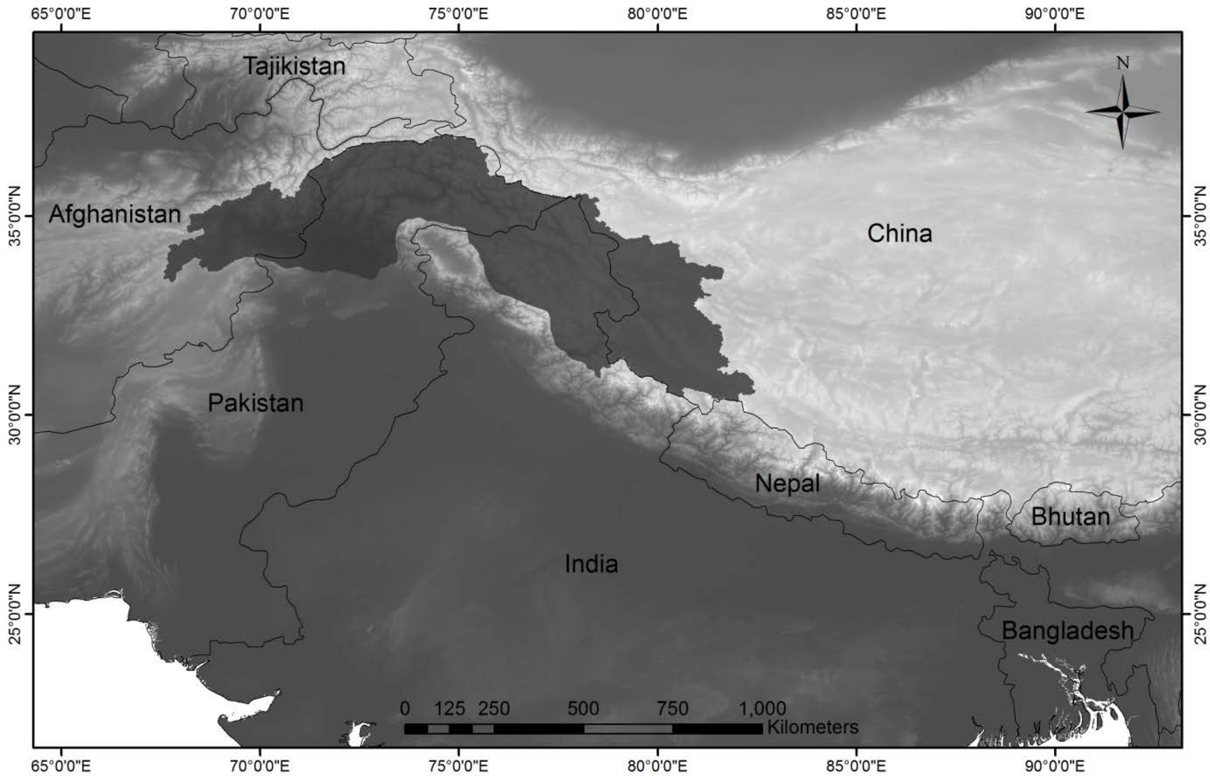

Figure 1: Map showing the glaciated portion of the Indus River watershed in dark grey. The Indus watershed follows the apex of the Himalayas and is partially found in Afghanistan, China, India, and Pakistan (2006; Kalnay *et al.*, 1996).

Concern over the potential effects of climate change on water resources has motivated research in the Indus River watershed during the past decade. Some studies have concentrated their efforts on the potential impact of climate change due to changes in glacial melt in individual basins based on idealized glacier size and conditions (Rees and Collins, 2006). Other research uses field evidence over small glacierized basins in isolated areas (Singh *et al*., 2006). Inconsistencies in measurement methods and the reporting of uncertainties in them make it difficult to compile individual studies for an understanding of the region as a whole.

Recent advances in remote sensing technology and the accumulation of remote sensing data in this part of the world, in addition to advances in glacier and climate modeling, make a self-consistent, regional study of the watershed possible. Projects and organizations like the Global Land Ice Measurements from Space (GLIMS), Tropical Rainfall Measuring Mission (TRMM), National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR), and the University of East Anglia Climate Research Unit (UEA CRU) provide remote sensing and reanalysis data, which give scientists numerical information without the need for measuring on location. This allows for scientific work in remote regions where prior study would have been highly improbable on a large scale.

Immerzeel *et al*. (2010) recently estimated glacial contribution to several major rivers across the Himalayas. They analyzed the trend in snow and ice mass balance over five river basins and concluded there is an overall mass loss. In the Indus watershed specifically they used glaciated area polygons to calculate the change in river discharge as a result of climate change (Patterson and Vaughn Kelso, 2011). Next, they calculated upstream river discharge for the present and future based on climate scenarios using hydrologic modeling. This information was compared to irrigation outputs to assess the water needs regionally. The results of their study showed that glaciers are very important to water resources over the region as a whole. It also indicated other significant inputs to water resources, such as precipitation and snowmelt, and demonstrated how these impacts could change with time. For the Indus, they conclude warming regional climate could be detrimental for water resources (Immerzeel *et al*., 2010).

The Immerzeel et al. (2010) study provides the first regional-scale estimate of glacier contribution to water resources and provides extremely valuable information about the water resources in the region. Their method also points to the need for additional work in the region. For example, the size of the polygons used in the Immerzeel et al. (2010) work does not allow for a delineation of which portions of the watershed could potentially be contributing the largest quantities of glacier melt. In addition, due to limitations in the glacier dataset they used, their results do not capture all of the glaciated area within the Indus watershed. Their results strongly motivate the importance of further work in the Indus watershed, in particular addressing some of the details of the smaller-scale spatial patterns in glacier melt across the region and the uncertainties that coincide with those calculations.

4. METHODS

The purpose of this study is to quantify glacier melt volume over the Indus watershed using a PDD approach for calculating glacier melt over large regions and highlight the uncertainties that attend that calculation. Furthermore, it delineates smaller regions or even individual glaciers of particular significance. This has the potential to help scientists determine where to focus their efforts in water resource studies involving glaciers in other locations. It will also help scientists better quantify the effects of changing climate on large glaciated regions.

4.1 Designing the Melt Model

Although many factors can contribute to glacier fluctuations, in this region glacier changes have been shown to be driven primarily by temperature (Ambach and Kuhn, 1985; Braithwaite, 1995; Kayastha, 2001; Rupper *et al*., 2009). Additionally, there is limited data available concerning energy inputs and mass changes at individual glaciers in the region. As such, a temperature-based PDD melt model was used for this study. This model calculates total melt volume at each glacier or glaciated area based on location, the temperature at that location, a regional temperature lapse rate, a melt factor, and the size of the glacier or glaciated area (equations 1 and 2).

The first step in the model was to determine the temperature at each glacier and glacierized area. Since weather station data at or near individual glacier areas is scarce to non-existent for the region, global gridded climate datasets were used. For each climate dataset, it was necessary to determine which temperature grid box each glacier is in and adjust that temperature to the temperature at the glacier elevation through regional lapse rates (Eq.1, Table 1) (Kalnay *et al.*, 1996).

$$T_{glacier} = T_{grid} + \Gamma\,(E_{glacier} - E_{grid}), \qquad \textbf{Eq. 1}$$

where T_{grid} is the temperature of the climate data grid cell in which the glacier lies, Γ is the adiabatic temperature lapse rate at that grid, $E_{glacier}$ is the mean elevation of the glacier, and E_{grid} is the elevation of the climate data grid cell.

Table 1: Description of variables used in the PDD model

Variables/ Constants	Description	Units
T_{grid}	Climate model gridded above ground air temperature	°C
$E_{glacier}$	Average elevation of the glacier	M
E_{grid}	Climate model gridded elevation	M
Γ	NCEP-NCAR Reanalysis gridded adiabatic lapse rate from upper air temperatures	°C m^{-1}
$T_{glacier}$	Air temperature of the glacier	°C
A	Glacier surface area available to melt	m^2
β	Degree day melt factor	m PDD^{-1} yr^{-1}
$V_{glacier}$	Glacier melt volume per year	m^3 yr^{-1}

The temperatures at each glacier provide necessary input for the PDD model of total annual melt volume (Eq. 2). (Eq. 2, Table 1) (Ambach and Kuhn, 1985; Braithwaite, 1995; Rupper *et al.*, 2009)

$$V_{glacier} = A\,\beta\,\sum(T_{glacier} > 0), \qquad \textbf{Eq. 2}$$

where the PDDs are the sum of all temperatures ($T_{glacier}$) greater than zero; β is the constant of proportionality relating melt to PDDs (melt factor), and A is the area of the glacier over which melt is occurring (Table 2). The individual melt volumes from each glacier area A were summed to calculate the total average glacier melt volume over the Indus watershed, or portions thereof.

4.2 Data Sources

Since the purpose of this study is to quantify melt volume and uncertainties associated with the melt calculation, multiple data sources needed to be utilized. To accomplish this, the procedure was followed using several glacier and global gridded climate datasets. Together they provide a more complete picture of glacier melt across the Indus watershed.

4.2.1 Glacier Information

Due to the difficult terrain, political nature, and remoteness of the glaciated portion of the Indus Watershed, as yet there is not a glacier database which designates all of the glaciers in the region. Therefore, to capture the fullest extent of the glaciers in the watershed, multiple databases were used, including the World Glacier Inventory (WGI), Global Land Ice Measurements from Space (GLIMS), and the Natural Earth glaciated areas (NE) (Figure 2). Due to some overlap in the datasets, complete use of each was limited so glacier area would not be overestimated.

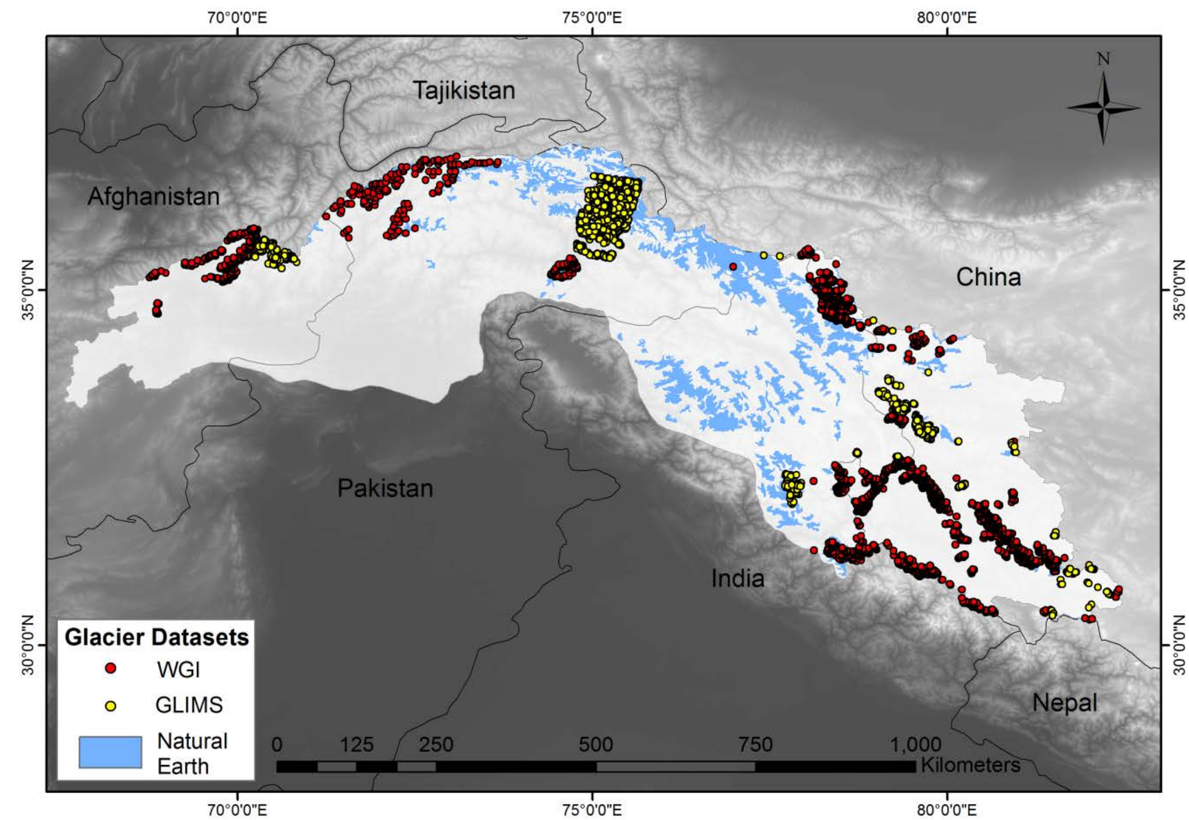

Figure 2: Location of glacier information from each of the three datasets with WGI in red, GLIMS in yellow, and NE in blue (2006; Kalnay *et al.*, 1996).

WGI

The WGI glacier information was used as the primary source for glacier data for this research. It is the longest standing dataset of the three, with the most complete information for individual glaciers over the Indus watershed. In this dataset, individual glaciers were represented by a single latitude and longitude coordinate. Information for each glacier includes latitude and longitude, area and area accuracy, date of the aerial photograph used to identify glacier areas, elevation, orientation, and length (NSIDC, 1999, updated 2009). Of the 2,606 glaciers in the Indus watershed, 148 did not contain elevation information. A 30 arc second grid resolution digital elevation model (DEM) was used to determine the approximate elevation of the glaciers at these locations (2006).

GLIMS

Global Land Ice Measurements from Space, also known as GLIMS is an international group of scientists collecting satellite images of glaciers from around the world (Kargel *et al.*, 2005). These images are analyzed to provide other researchers with information about locations of glaciers and their spatial and temporal changes. Although incredibly beneficial, this dataset is far from complete in many regions, including the Indus watershed (Immerzeel *et al.*, 2010). So far, GLIMS contains 1,298 glaciers within the Indus watershed that were used in this study (Figure 2) (Bajracharya, 2008; Berthier, 2006; Haritashya, 2005, 2006, 2007; Nosenko, 2005). Since it contains files of individual glaciers within the study area but no elevation data, it was designated as the secondary source for glacier data.

GLIMS data can be accessed as an ESRI polygon shapefile. Each polygon is associated with two glacier area fields: area and database area. For this region the area was often incomplete, while the database area contained information for each glacier, so the database area value was used in calculations. Since the PDD model is designed to make calculations based on a point location and elevation for every glacier, the centroid was calculated for each polygon, and the latitude and longitude of the centroid was used to represent the glacier location. The GLIMS glaciers in this region also lacked information in the elevation data fields, so this was determined using a one kilometer resolution DEM at the location of each centroid (2006).

NE

Unlike the WGI and GLIMS glacier data, the NE database does not differentiate between individual glaciers. Instead it marks the boundaries of large glaciated areas, which, in some cases, are tens of kilometers in size. Due to this, they are the tertiary glacier dataset. The NE glaciated areas are compiled in a polygon shapefile available on the Natural Earth website (www.naturalearthdata.com). Although designed for cartographic purposes, this dataset provides the largest, and potentially most complete glaciated area for the region (Patterson and Vaughn Kelso, 2011). The glaciated area polygons were originally derived from the Digital Chart of the World, a map designed to support flight crews, military operations planners, intelligence briefings, and other activities (1992). The information incorporated into the map is from a series of years between the 1960s and the 1990s.

To use this data in the PDD model and more closely capture the elevation and temperature at different places within each polygon, it was necessary to separate the glaciated areas into smaller polygons of less than 36 km^2. These smaller polygons do not represent individual glaciers. The centroid of each of these areas was determined, and became the polygons' latitude and longitude locations. The approximate elevation of the points was determined using the values of a DEM with a one kilometer grid scale at the latitude and longitude of the points (2006).

Once each of the glacier datasets had information in the correct format, the PDD model could be applied to calculate melt over each glacier or glaciated region.

4.2.2 Temperature Data

After the glacier data (latitude, longitude, surface area, and elevation) were compiled, equation 1 was applied to calculate the temperature at each glacier. However, the glaciated portion of the Indus watershed is so remote, there is little data available from local weather stations to depict the actual temperature at each glacier. As a result, indirect temperature datasets were used in this study. Numerous organizations have used different methods to provide global temperature datasets. Those used in this study include the National Centers for Environmental Protection (NCEP), National Center for Atmospheric Research (NCAR), and the University of East Anglia Climate Research Unit (UEA CRU). These were chosen because it was possible to determine the influence of choice of model and grid resolution on the result.

UEA CRU CL 2.0

The UEA CRU has developed several climate models with information around the globe. For these they use global weather station data to create climate grids at several spatial scales (Mitchell *et al*., 2003; Mitchell and Jones, 2005; New *et al*., 2002). The CRU CL 2.0 global dataset incorporates information about monthly mean surface air temperature at a ten minute latitude/longitude grid scale (New *et al.*, 2002). The global temperature was interpolated using information from weather stations from 1961 to 1990. Of the three climate datasets used in this research, the CRU CL 2.0 had the finest grid scale. To facilitate comparison between the different climate datasets, this model was used as a control against which all other datasets are compared.

UEA CRU TS 2.1

Prior to creating the ten minute grid scale dataset, UEA CRU constructed a 0.5 degree gridded temperature dataset. Subsequently, several versions of climate data were constructed at this grid scale. For this study the CRU TS 2.1 was used (Mitchell and Jones, 2005). This monthly mean air temperature dataset has values for surface land area temperature from 1901-2002 (Mitchell and Jones, 2005).

NCEP/NCAR 40 year reanalysis

Unlike the UEA CRU, not all global gridded climate information comes from weather stations. The National Centers for Environmental Protection (NCEP) and the National Center for

Atmospheric Research (NCAR) collaborated to design a global reanalysis gridded temperature dataset (Kalnay *et al.*, 1996). It has a 2.5 degree grid cell resolution for 1957-1996. The data used in the reanalysis model incorporates information from several different sources including satellites, land surface, ships, and aircraft. This information was used to reconstruct global climate in the past as well as extrapolate climate for the future.

4.2.3 Lapse Rates

Since the temperature information used in this study came from global gridded temperature datasets, the glaciers were often not at the same elevation as the temperature grid cells. To compensate for this difference, adiabatic temperature lapse rates were used to calculate the temperature at each glacier. The lapse rates are from the NCEP/NCAR 40 year reanalysis, as this is the only dataset for which lapse rate information is provided. The NCEP/NCAR lapse rate was applied to each temperature dataset to calculate positive degrees at each glacier due to this (Kalnay *et al.*, 1996). Since the NCEP/NCAR data was at 2.5 degrees, the lapse rates used were at a coarser grid scale than the UEA CRU climate data.

4.2.4 Melt Factors

The temperature at each glacier derived from the gridded datasets and lapse rates was used in conjunction with a melt factor to calculate the melt rate at each glacier. Due to the size of the study region, the large number of glaciers, and the inaccessibility of the glaciers, melt factors have not been calculated for each glacier. However several studies have calculated melt factors for glaciers throughout southern Asia (Table 6) (Kayastha, 2001; Kayastha *et al*., 2000a; Kayastha *et al*., 2000b; Singh *et al*., 2000a; Singh *et al*., 2000b; Zhang *et al*., 2006). Since there is a range of melt factor values throughout the region, the mean melt factor was calculated by averaging all of the ice melt factors. The maximum (minimum) values were determined by averaging all melt factors greater (less) than one standard deviation above (below) the mean (Table 6). Although both snow and ice melt factors have been calculated in the region, this study uses the ice melt factors for several reasons. For example, there are too few recorded regional snow melt factors available to perform reasonable statistics. Additionally, during summer months, the season of highest glacier melt, snow has largely melted from the glacier surface. Therefore, the predominant source of melt during the season of greatest melt for most glaciers comes from the ablation of firn and glacier ice. Finally, the minimum melt factor calculated would take into account primarily snow-covered glaciers.

4.3 PDD Model Scenarios

With the PDD model in place and data available, the aims of this study can be addressed. One aim is to determine uncertainties in the PDD model outputs. This is determined by using multiple climate datasets which test the sensitivity of the results to climate data source and grid size and by running the model using four different scenarios (Table 2). First, a mean melt volume for the entire watershed was calculated using mean temperatures and lapse rates with mean melt factors and mean glacier area from the various datasets. Second, a maximum melt volume was calculated from a decreased lapse rate with increased PDD melt factors and a maximized glacier area available to melt. Third, a minimum glacier melt volume was calculated by increasing the lapse rates while decreasing the PDD melt factor and the glacier area available to melt. Lastly, errors in the PDD model inputs were assumed to be random. To do this, a white noise time series was determined using the mean of glacier area available to melt, lapse rate, and melt factor with a given standard deviation in each variable. Results were determined for 250 combinations of lapse rates, melt factors, and glacier ablation areas for each glacier (Table 2).

Table 2: Differences in degree-day model scenarios

Scenario	Temperature Lapse Rate Γ (C/km)	Degree Day Melt Factor β (m/PDD)	Glacier Area (km)
Mean	NCEP/NCAR	0.008	WGI*0.75
Minimum	NCEP/NCAR +1	0.0037	WGI*0.40
Maximum	NCEP/NCAR – 1	0.0138	WGI*1.00
Randomized	NCEP/NCAR +/- 0.5	0.008 +/- 0.003	WGI*(+/- 0.05)

In addition to the current contributions of glacier melt to the watershed, it is important to understand the impacts of future climate change on these glaciers. Climate model simulations over the globe available from the Intergovernmental Panel on Climate Change (IPCC) provide estimates of future climate scenarios (Cruz *et al*., 2007). These were used with this PDD model to calculate future impacts of glacial melt in the Indus watershed. The Special Report on Emission Scenarios (SRES) future temperature change results suggested different increases in temperature across Asia. In some locations the temperature rise could be as small as 0.6 °C but in others as much as 2 or 3 °C in Asia over the next 30 years. Since a range of values are possible, the mean PDD model scenario was applied using UEA CRU CL 2.0 assuming three increasing temperature scenarios: 0.5, 1, and 2 °C (Cruz *et al*., 2007). Each temperature increase was applied equally across the watershed. It was assumed that the general trend in comparison between UEA CRU CL 2.0 and the other climate datasets would be similar, so the increasing temperature scenarios were not applied to the other climate datasets. Further study would be beneficial to confirm this.

5. RESULTS

The PDD melt model, with its respective scenarios, provides information about the current and future state of glacier melt in the Indus watershed (Table 2). With an understanding of the melt model, expected trends in glacier melt volume can be anticipated. For example, glaciers with both large surface area and warm temperature (usually at lower elevations) are expected to contribute the greatest proportions of melt volume to the watershed as a whole.

5.1 Elevation

Although elevation can play a different role in temperature depending on the location of glaciers, in general, glaciers at lower elevations will experience warmer temperatures. Therefore, the elevation plays a significant role in determining glacier melt volume (equation 2). For the Indus watershed, the average elevation of known glaciers from the WGI and GLIMS databases is 5,584 and 5,202 meters above sea level respectively, with standard deviations of 530 and 568 meters. However, the elevation of individual glaciers varies between 3000 and 7500 meters (Figure 3). There are relatively low elevation glaciers (less than 5,000 m) throughout the watershed, but the majority of them are found in the north and northwest, predominantly in Afghanistan and Pakistan (Figure 4, Table 3). Since the Natural Earth glaciated areas are not separated into individual glaciers it is difficult to distinguish glacier elevations from this dataset. The low elevation polygons in the NE glaciated areas are largely found in Pakistan, but some are also found in the southern portion of the watershed in India (Figure 4).

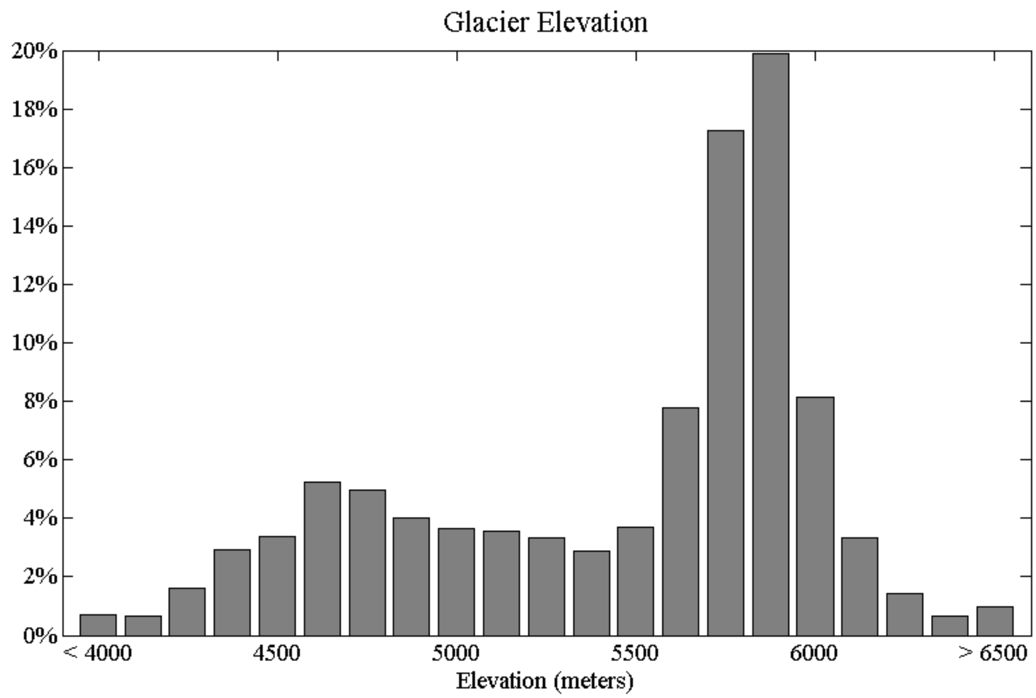

Figure 3: Histogram of glacier elevation in meters for the WGI and GLIMS glaciers

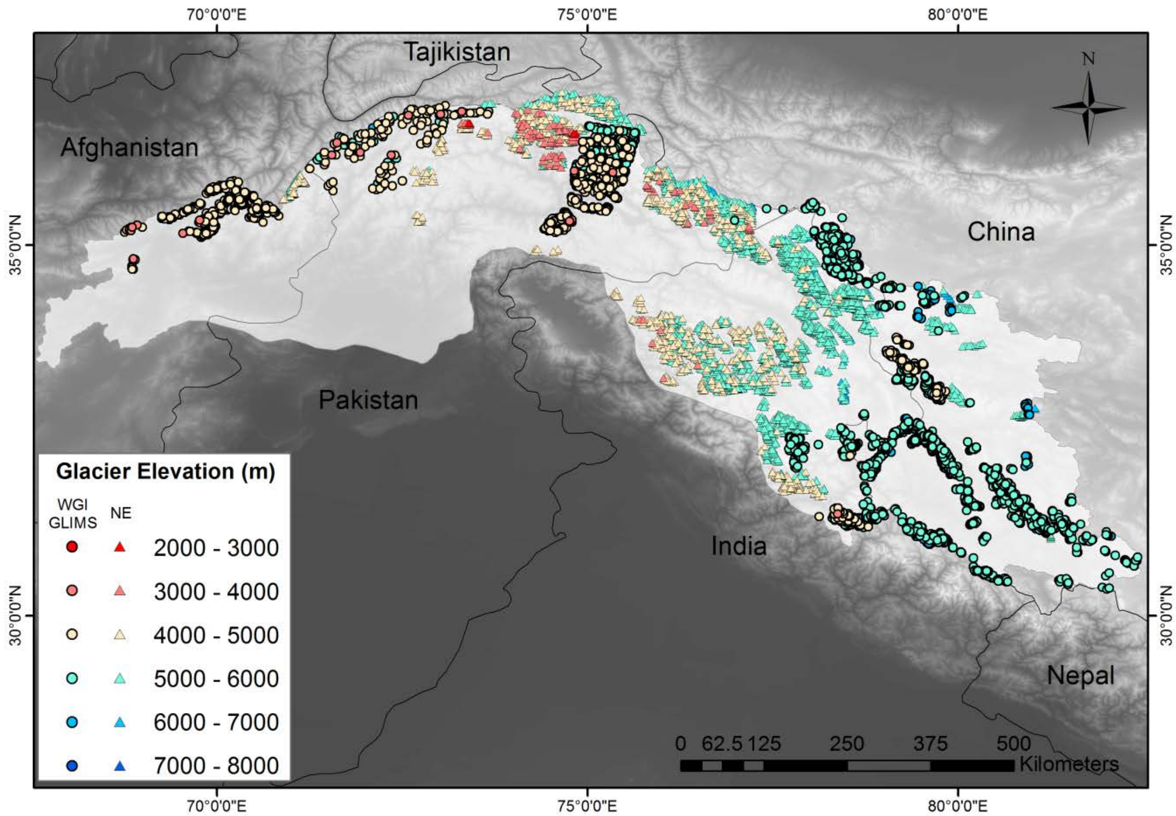

Figure 4: Spatial distribution of glacier elevation throughout the Indus watershed. WGI and GLIMS glaciers are represented by circles while NE glaciated areas are designated by triangles. The NE glaciated areas do not represent individual glaciers (2006; Kalnay *et al*., 1996).

Table 3: Elevation above sea level of glaciers from WGI and GLIMS datasets according to country

	Average (m)	Minimum (m)	Maximum (m)
Afghanistan	4506	3888	5025
China	5730	4214	6535
India	5630	3270	6464
Pakistan	5117	3374	7322

5.2 Area

Like elevation, the glacier area available to melt is a significant factor in melt volume. However, because change in area goes as a square, statistically it has the greatest correlation with glacier melt volume and the largest influence on melt volume model outputs of all the PDD model variables (equation 2). This also implies that errors in glacier area will have the greatest impact on melt volume calculations. The three glacier datasets used in this PDD model account for a total glaciated area of more than 47,000 km^2 (Table 4). However, each glacier dataset and country contains very different percentages of the total glaciated area of the watershed. Nearly 8% of the glacier area in this research is accounted for in glaciers from the WGI, approximately 5% is accounted for by GLIMS, and the remaining 87% is accounted for by the NE glaciated areas (Table 4). When analyzed by country, less than 1% is located in Afghanistan, nearly 7% is found in China, 52% is located within India, and 40% is found in Pakistan (Table 4). These values have some potential error associated with them. The WGI and GLIMS glacier area values were determined using aerial photographs collected over several decades (Table 5). The earlier aerial photographs have a greater potential for error since glaciers have larger possibility of varying in size over longer timescales.

The position of large glaciers is important to calculations that determine where the majority of melt volume is contributed from. The WGI and GLIMS datasets were analyzed to show the locations of glaciers with relatively large average glacier surface area. The vast majority of glaciers are less than 5 km^2, but some are larger than 400 km^2 (Figure 6). Spatially, the country with the most glaciers larger than 5 km^2 is Pakistan followed by China, India, and lastly Afghanistan (Figure 5).

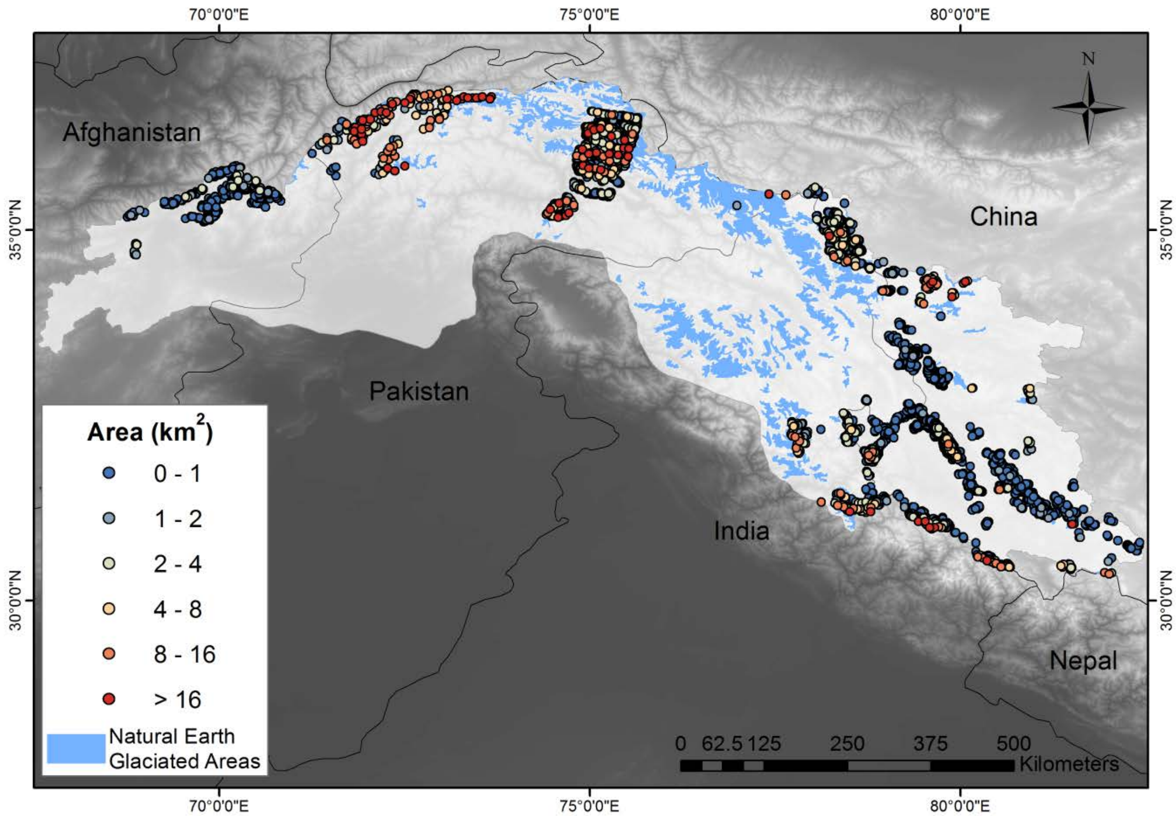

Figure 5: Size of individual glacier surface areas across the watershed. The WGI and GLIMS glaciers are represented by circles while the NE glaciated areas are represented by blue polygons (2006; Kalnay *et al*., 1996).

Table 4: Total glacier surface area by country and glacier dataset in square kilometers

Glacier Area by country and dataset (km^2)					
	WGI	*Glims*	*NE*	***Total***	***% of whole***
Afghanistan	127.8	51.1	235.3	414.2	0.87%
China	1577.3	134.8	1592.8	3305.0	6.98%
India	358.5	147.3	24259.5	24765.4	52.30%
Pakistan	1650.9	2117.9	15096.6	18865.4	39.84%
Total	3714.6	2451.2	41184.3	47350.1	
% of whole	7.84%	5.18%	86.98%		

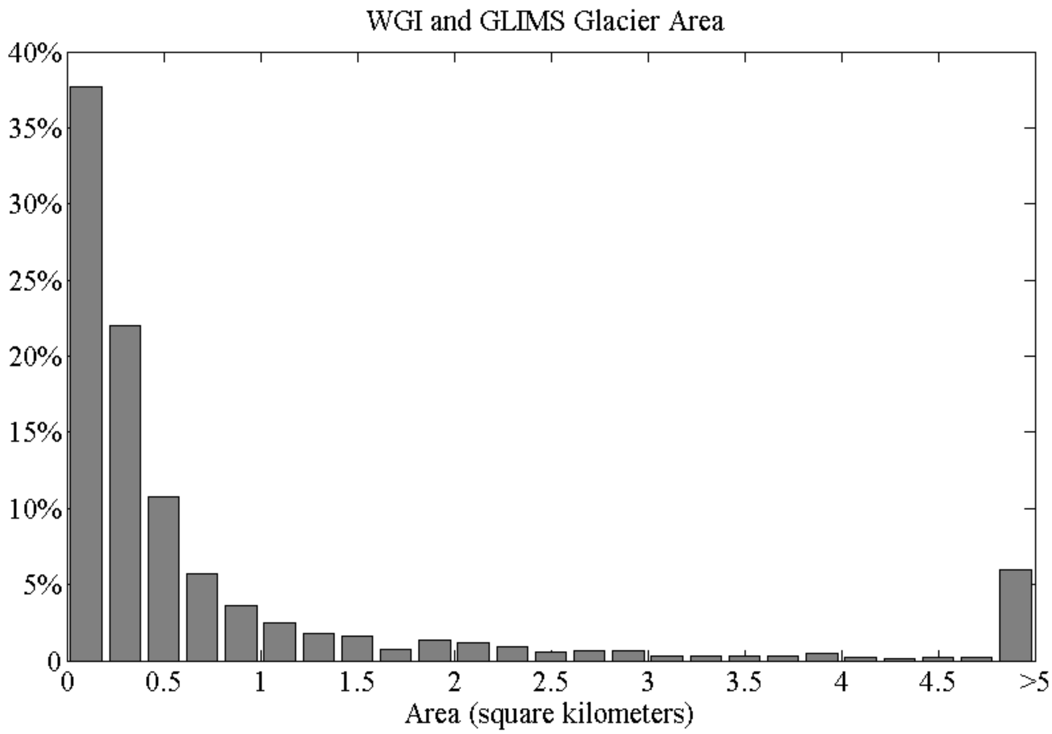

Figure 6: Histogram of average glacier surface area using WGI and GLIMS glaciers

Table 5: Date of collection of aerial photographs used to determine WGI and GLIMS glacier surface area by decade.

Year	# of glaciers
1930's	6
1950's	10
1960's	28
1970's	807
1980's	1608
2000's	875
Unknown	542
Total	***3876***

5.3 Melt Factors

While the glacier surface area is indicative of how much ice is available to melt, melt factors determine how much melt should be anticipated given the regional conditions, or the expected melt per degree day over a given time period. Hence, melt factors are essential for determining the melt using a PDD model (equation 2). Melt factor data used in this research came from several different studies in the region (Table 6). The mean, minimum, and maximum ice melt factors for this study are 8.0, 3.7 and 13.8 m PDD^{-1} yr^{-1} respectively.

Table 6: Melt factor calculations from the literature and calculated melt factors used in the PDD model.

Glacier	Ice*	Snow*	Citation	Glacier	Ice*	Snow*	Citation
Rakhiot	5		Zhang et al, 2006	Yala	8		Kayastha, 2003
	13.3	5.9			10.5		
	13.2				9.3		Kayastha 2001
	12				10.1		Kayastha 2002
	3.4			Xiao Dongkemadi	13.3		Kayastha, 2003
	5.9				14.2		
	6.4			July 1st	5.5		Kayastha, 2003
	2.6				7.2		
	4.3				8.8		
	3			Dokriani	7.4	5.7	Singh, 2000
	4.7				8	6.4	Singh, 2001
	3.6					5.9	Singh and Kumar, 1996
	13.8				7.4	5.7	Singh et al., 2000a,b
	7.2			AX010	8.1	7.3	Kayastha et al 2000a
	9				8.8	8.7	
	8.5					11.6	
	7.3	3.1		Khumbu	16.9		Kayastha et al 2000b
	4.5				6.6		
	7			***Mean***	8.0	* Melt factor units are in m PDD^{-1} yr^{-1}	
	4.5			***Standard Deviation***	3.4		
	7.3			***Maximum***	13.8		
	8.6	3.4		***Minimum***	3.7		

5.4 Temperature

As stated previously, to calculate the glacier melt volume, with its respective uncertainty, temperature outputs for three climate models were used. Since each climate dataset was calculated using different methods, resolutions, or both, the spatial variability in temperature across the watershed varies from one dataset to another. UEA CRU CL 2.0 was chosen as a control for temperature calculations since it was calculated at the finest grid scale. The control was subtracted from each other dataset for comparison (Figure 8). Figure 7 shows a comparison between the mean PDD model outputs for each temperature dataset. The correlation coefficient was also calculated for the comparison of each dataset (Table 7).

Table 7: Calculated correlation coefficients by comparing temperature values from the climate datasets

Correlation of temperature data			
	UEA CRU CL 2.0	*NCEP/NCAR*	*UEA CRU TS 2.1*
UEA CRU CL 2.0	1.000	0.880	0.875
NCEP/NCAR	0.880	1.000	0.763
UEA CRU TS 2.1	0.875	0.763	1.000

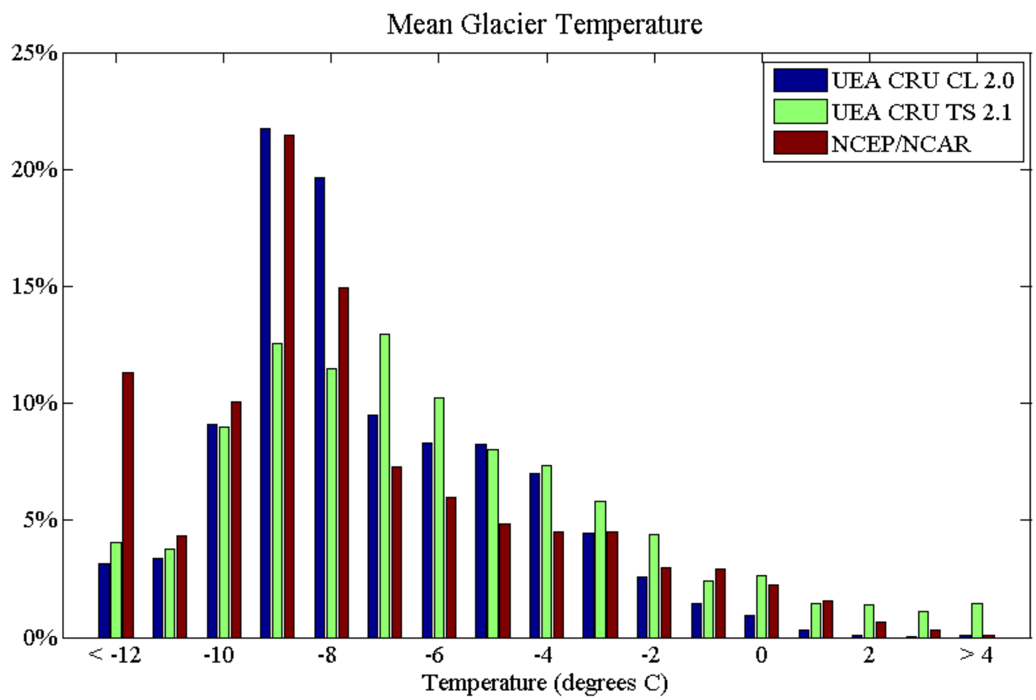

Figure 7: Histogram of mean temperature at WGI and GLIMS glaciers using each of the three climate models: UEA CRU CL 2.0, UEA CRU TS 2.1, and NCEP/NCAR Reanalysis

Table 8: Calculated correlation coefficients and confidence intervals from comparing the climate dataset temperature values. All correlation values are statistically significant at 0.5 confidence level.

	Correlation	**Statistically significant**	**95% Confidence Interval**
UEA CRU CL 2.0 to NCEP/NCAR	0.880	yes	$0.875 \leq \rho \leq 0.885$
UEA CRU CL 2.0 to UEA CRU TS 2.1	0.875	yes	$0.870 \leq \rho \leq 0.880$
NCEP/NCAR to UEA CRU TS 2.1	0.763	yes	$0.753 \leq \rho \leq 0.772$

5.4.1 Statistical and Spatial PDD Model output comparisons

To give an idea of how similar the temperature datasets are to each other, correlation coefficients were calculated. Each dataset comparison had a correlation coefficient of greater than 0.76, and the highest correlations were found when comparing datasets to the control (Table 7). Two tailed t-tests were conducted for the correlation coefficients to determine if the values are statistically significant at a 95% confidence level (Table 8). Each correlation coefficient was found to be statistically significant. The 95% confidence interval was also calculated for each comparison (Table 8). It is important to note these statistics do not take into account autocorrelations with each dataset.

Since UEA CRU CL 2.0 was used as the control dataset, these results were examined first. Spatially, the glaciers which have annual average temperatures greater than 0 ºC are found throughout the watershed in every country except Afghanistan (Figure 8). The warmest glaciated areas in particular are largely found in Pakistan. When considering only glaciers rather than glaciated areas, glaciers with mean annual temperature above the freezing point are found throughout Pakistan, along the south eastern portion of the glaciated watershed in India, and in the west central China in the glaciated portion of the watershed. Glacier temperatures ranged between -24 °C and 11 °C, with a mean temperature of -7.3 °C.

Table 9: WGI and GLIMS glacier temperature for each of the climate datasets using the mean, minimum, and maximum PDD model runs from Table 2

	UEA CRU CL 2.0 (°C)	**UEA CRU TS 2.1 (°C)**	**NCEP/NCAR (°C)**
Mean Run			
Mean	-7.3	-6.2	-7.6
Maximum	9.3	14.5	9.9
Minimum	-21.3	-20.9	-23.0
Minimum Run			
Mean	-6.9	-5.6	-7.3
Maximum	7.8	14.0	8.7
Minimum	-19.0	-18.5	-20.9
Maximum Run			
Mean	-7.7	-6.9	-7.9
Maximum	10.7	15.0	11.1
Minimum	-23.5	-23.4	-25.1

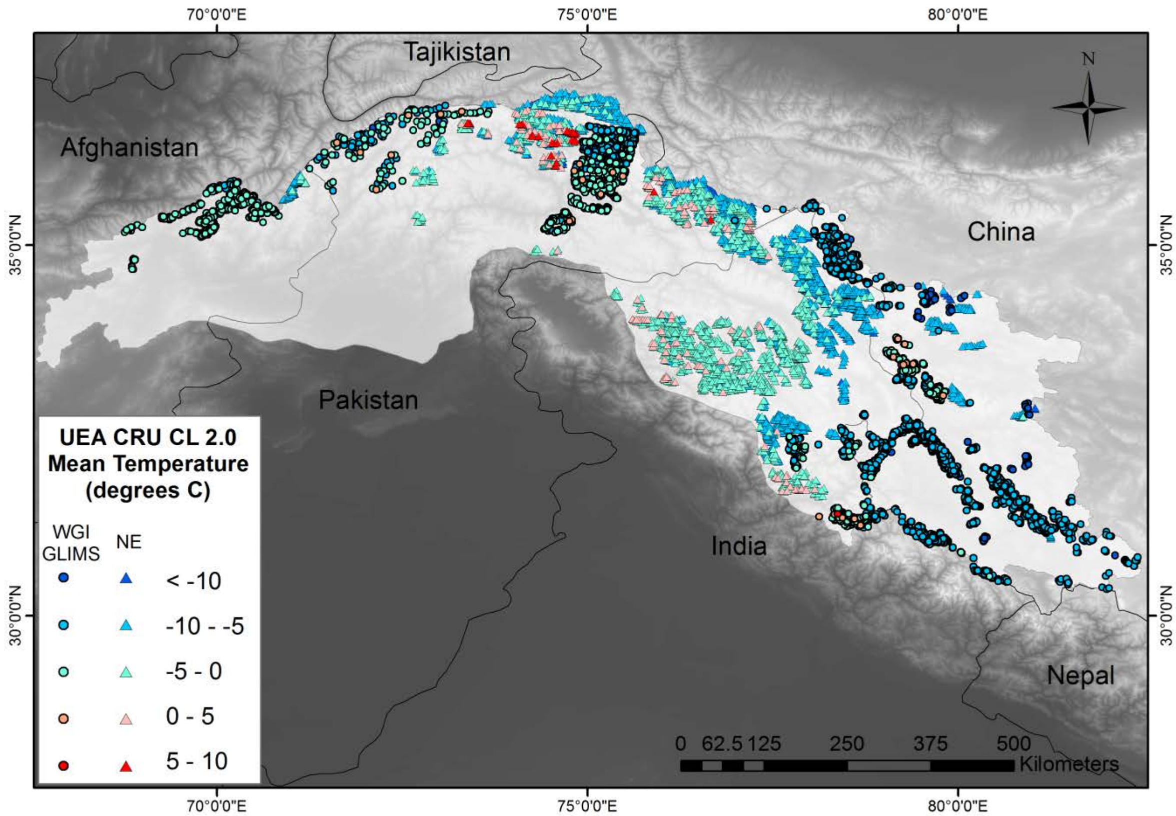

Figure 8: Mean annual temperature at WGI and GLIMS glaciers and NE glaciated areas using UEA CRU CL 2.0. WGI and GLIMS are represented by circles while NE is depicted with triangles (2006; Kalnay *et al*., 1996).

On average, the magnitudes of temperatures using UEA CRU TS 2.1 are warmer than the control, but the spatial pattern in temperatures are very similar, with a correlation coefficient of 0.875. One distinct exception is in the southernmost edge of the glaciated watershed in India where this PDD model shows temperatures more than 5 ºC warmer than the control. Based on this, a similar pattern in melt is expected between this dataset and the control, with an exception in the southern region of India. Numerically, the annual glacier temperatures using this dataset are greater than the control with a larger range from maximum to minimum (Table 9). As a result, melt volumes using this dataset are expected to be greater than the control.

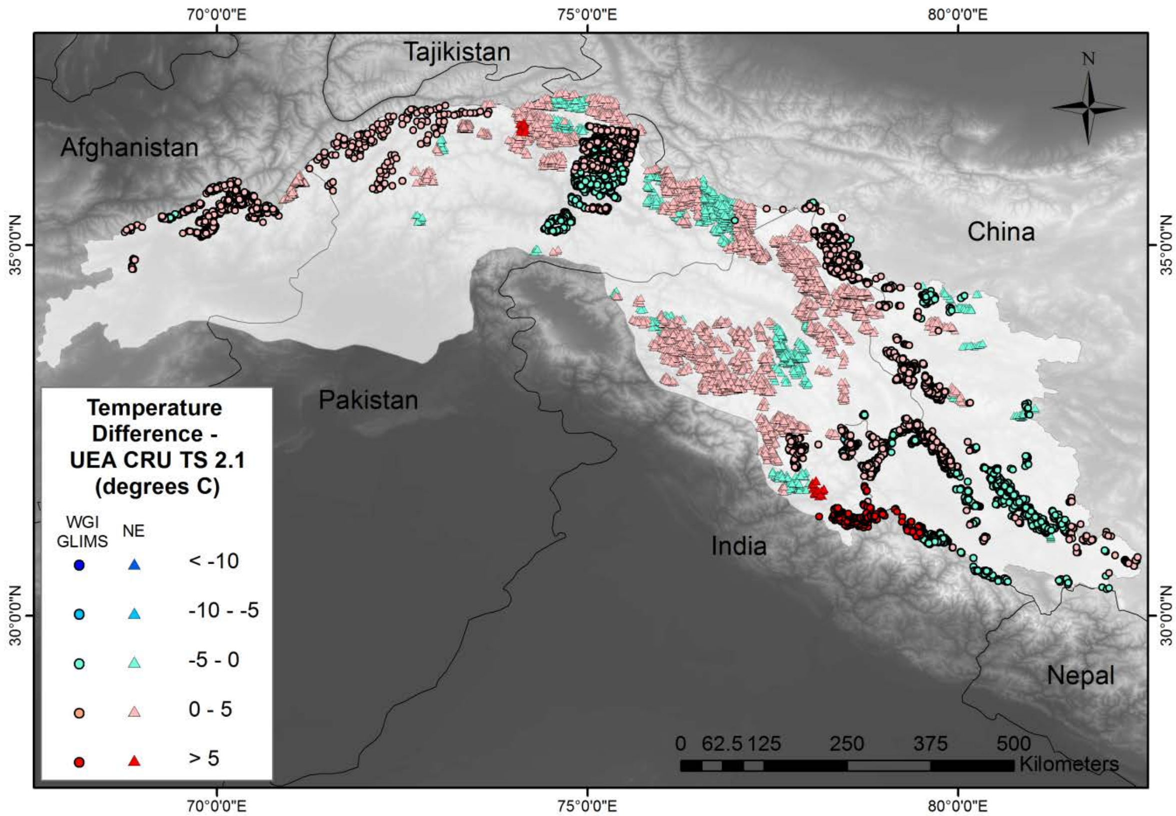

Figure 9: Mean temperature at WGI and GLIMS glaciers and NE glaciated areas using UEA CRU TS 2.1. WGI and GLIMS are represented by circles while NE is depicted with triangles (Kalnay *et al*., 1996; USGS, 2006)

Similar to the UEA CRU TS 2.1, the NCEP/NCAR reanalysis temperatures are highly correlated with the control, with a correlation coefficient of 0.88. However, unlike UEA CRU TS 2.1, this climate model yields more glaciers at cooler average temperatures (Figure 7, Table 7). Numerically, the glacier temperature range using this dataset is close to or lower than the control, so melt volumes calculated using this dataset are expected to be lower than the control (Table 9).

Spatially, there are some significant differences between NCEP/NCAR and the control datasets as well. Like UEA CRU TS 2.1 the temperature at glaciers in Afghanistan tend to be warmer than the control, but the westernmost glaciers in the Afghanistan portion of the glaciated watershed are more than 5 °C warmer from NCEP/NCAR data. Temperatures in the Pakistan portion of the watershed were varied with glaciers on the northern edge being predominantly 5 °Ccooler than the control, and on the southern portion glaciers tend to be 5 °C warmer. In India, the glaciers are predominantly cooler except small bands on the northern and southern borders of the glaciated watershed. In China the glacier temperature appears to be varied throughout.

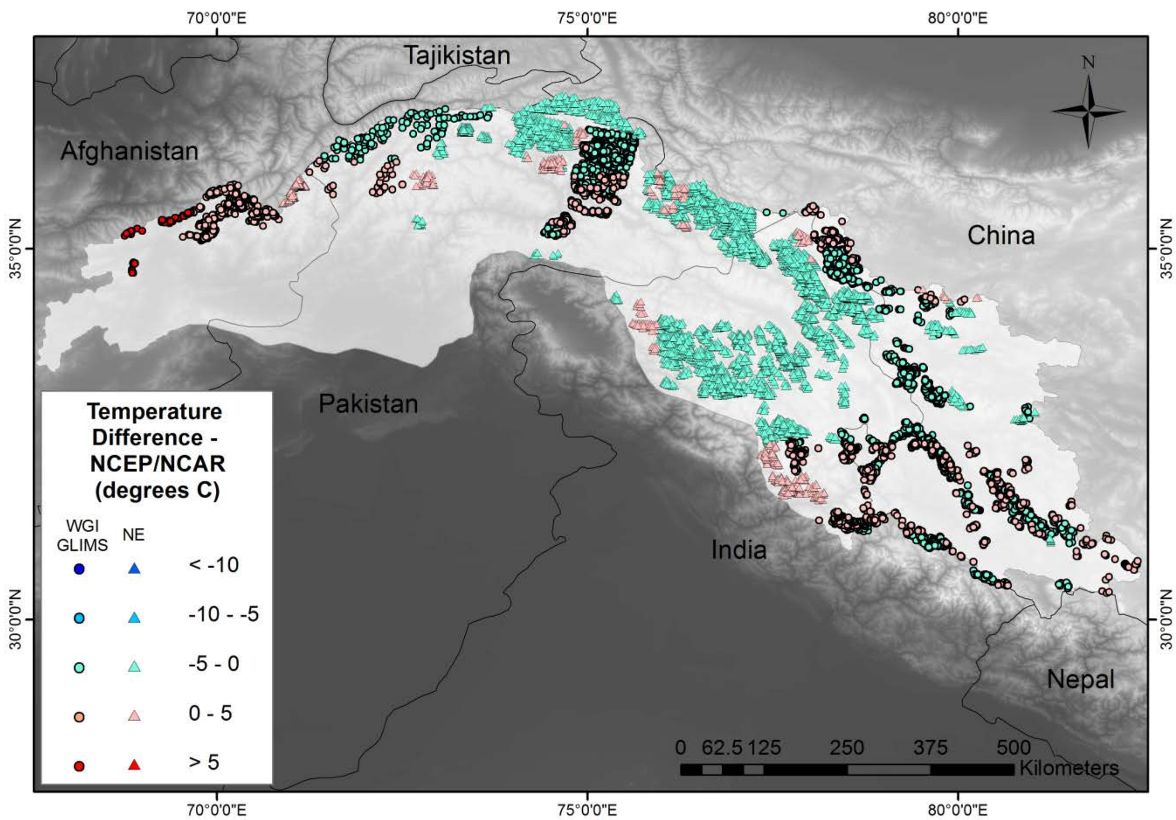

Figure 10: Mean temperature at WGI and GLIMS glaciers and NE glaciated areas using NCEP/NCAR Reanalysis. WGI and GLIMS are represented by circles while NE is depicted with triangles (2006; Kalnay *et al.,* 1996)

Overall, these spatial patterns in glacier elevations, glacier areas, and temperatures give rise to spatial patterns in melt volume. Even without a PDD model to quantify melt, an analysis of glacier size and location provides an a priori idea of locations where melt volume will be greatest. Given that most large and low elevation glaciers are found in Pakistan, and a large percentage of glacier area is in Pakistan, it should be expected that Pakistan will have the largest melt volume of any country in the Indus watershed. This also coincides with the location of glaciers at warm temperatures. Despite variations in the temperature from different climate models, glaciated areas in Pakistan tend to be relatively warm. However, the differences in the magnitude and pattern in temperature datasets will result in differences in the magnitude and spatial pattern in melt volume across the watershed.

5.5 Melt Rates

The melt rate calculated for each glacier is a function of the PDD and the melt factor (equation 2). Since PDD is determined by the temperature at each glacier, the melt calculations vary depending on which climate dataset is used in the PDD model (Figure 11, Table 10).

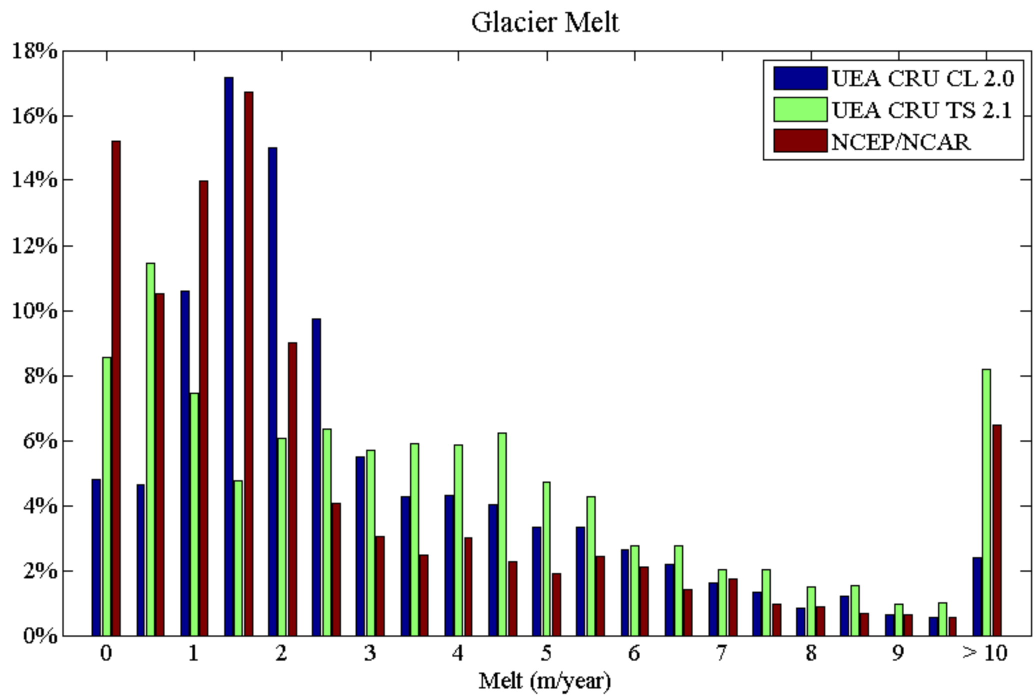

Figure 11: Histogram of glacier melt rate for individual WGI and GLIMS glaciers in meters per year (with the y-axis representing the percentage of glaciers in the watershed with a given melt rate)

Table 10: Melt rate calculated using the three climate datasets and the mean, minimum, and maximum PDD model runs

	UEA CRU CL 2.0 (m/yr)	UEA CRU TS 2.1 (m/yr)	NCEP/NCAR (m/yr)
Mean Run			
Mean	3.93	5.00	3.12
Minimum	0	0	0
Maximum	27.13	42.31	28.92
Maximum Run			
Mean	6.44	7.95	5.45
Minimum	0	0	0
Maximum	53.85	75.60	55.88
Minimum Run			
Mean	1.92	2.52	1.46
Minimum	0	0	0
Maximum	11.03	18.87	11.92

5.5.1 Spatial PDD Model output comparisons

As in the temperature calculations, UEA CRU CL 2.0 was used as a control. The melt rate calculated using the control climate dataset yielded spatially variable results, as expected from the spatial variability in temperatures at each glacier (Figure 12). Glaciers and glaciated areas with relatively high melt rates were found in many places across the watershed. Relative high melt was found in every country in small pockets of glaciers and glaciated areas (Figure 12). Numerically, the mean melt rate varied from 0 m/year to 28 m/year with an average of 3.93 m/year (Table 10).

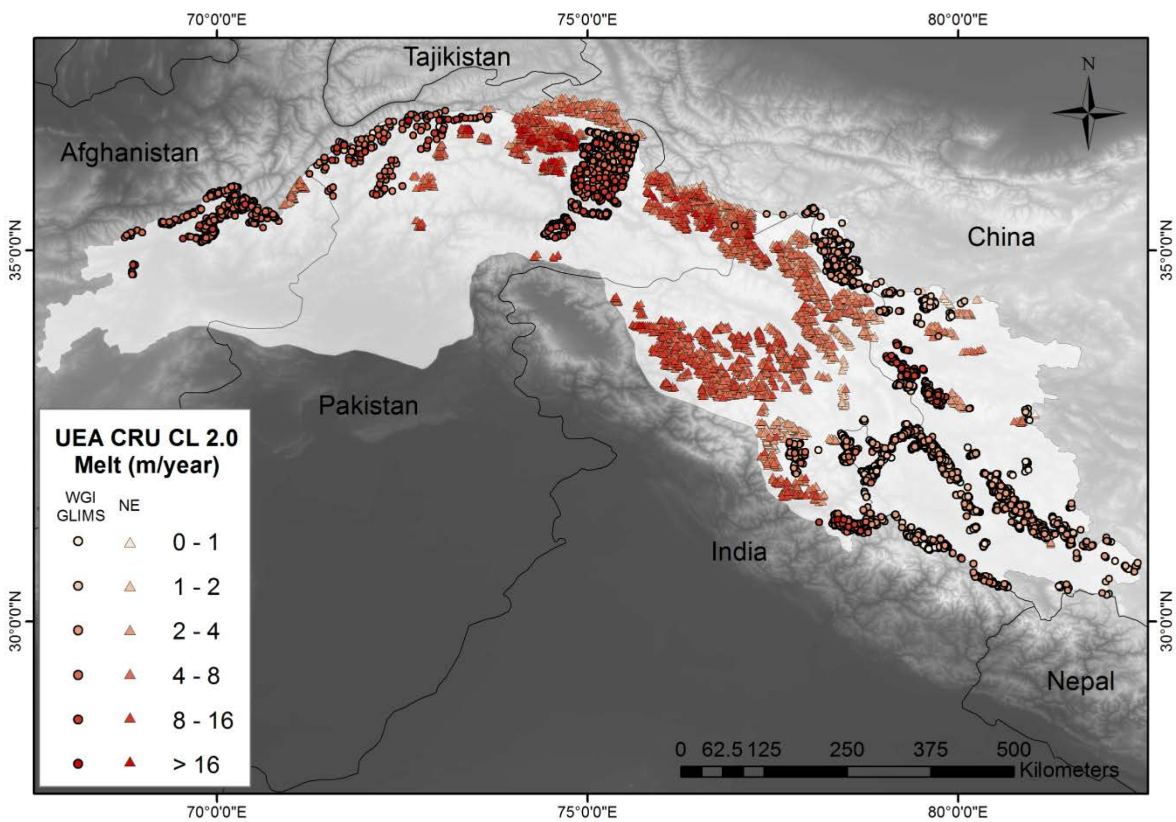

Figure 12: Map of melt rate from glaciers and glaciated areas using the UEA CRU CL 2.0 temperature data, in meters per year. Circles represent WGI and GLIMS glaciers while triangles depict NE glaciated areas (2006; Kalnay et al., 1996).

By comparison, the melt rate results from UEA CRU TS 2.1 differ significantly from the control, but the variations are not uniform (Figure 13). There are relatively small pockets of both higher and lower melt values similar to the pockets of higher and lower temperature. Melt in Afghanistan, northern Pakistan, and most of India tends to be larger for this dataset than the control because this climate dataset indicates warmer temperatures at these locations. There are pockets of lower melt in China and the southern portion of the watershed in Pakistan. The largest high melt differences are found in the southern part of the watershed in India where glacier melt rate is more than 9 m/year larger than the control, where the largest difference in temperature also occurs (Figure 13). Numerically, the mean melt varied between 0 m/year and 43 m/year, with an average of 5 m/year (Table 10). These values are larger than the control in all PDD model scenarios. This is expected considering the dataset suggests much warmer temperatures across the watershed.

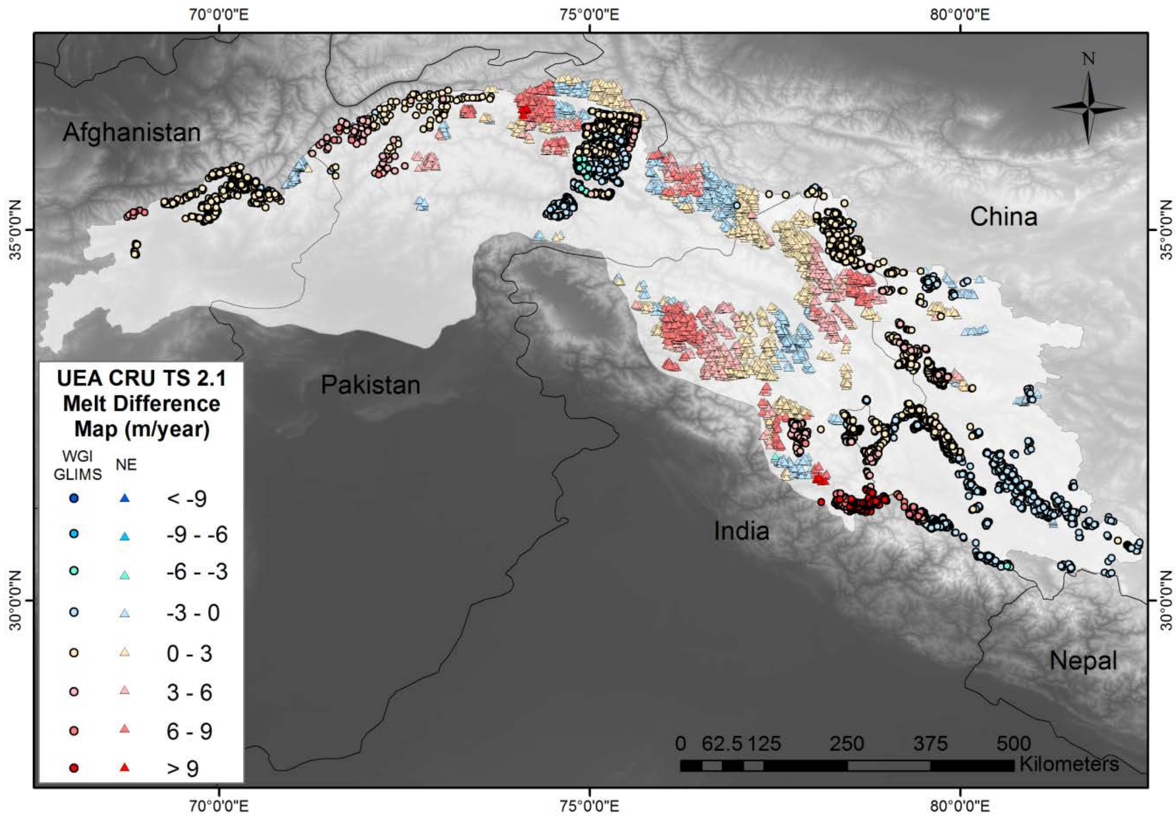

Figure 13: Map of difference in melt rate from glaciers and glaciated areas using the control subtracted from the UEA CRU TS 2.1 temperature data in m/year. Circles represent WGI and GLIMS glaciers while triangles depict NE glaciated areas (2006; Kalnay *et al.*, 1996)

The mean melt rate calculated using the NCEP/NCAR 40 year reanalysis dataset has different spatial variation from the control than UEA CRU TS 2.1. In most glaciated areas, this dataset yields lower melt rates than the control because the temperatures in this dataset are often cooler (Figure 14). Exceptions are predominantly found in glaciated locations in Afghanistan as well as the southernmost portion of the glaciated watershed in India. Numerically, the mean melt rate varied between 0 m/year and 29 m/year with an average of 3.12 m/year (Table 10). These melt rate values are lower than the control, as expected given the temperature dataset is cooler.

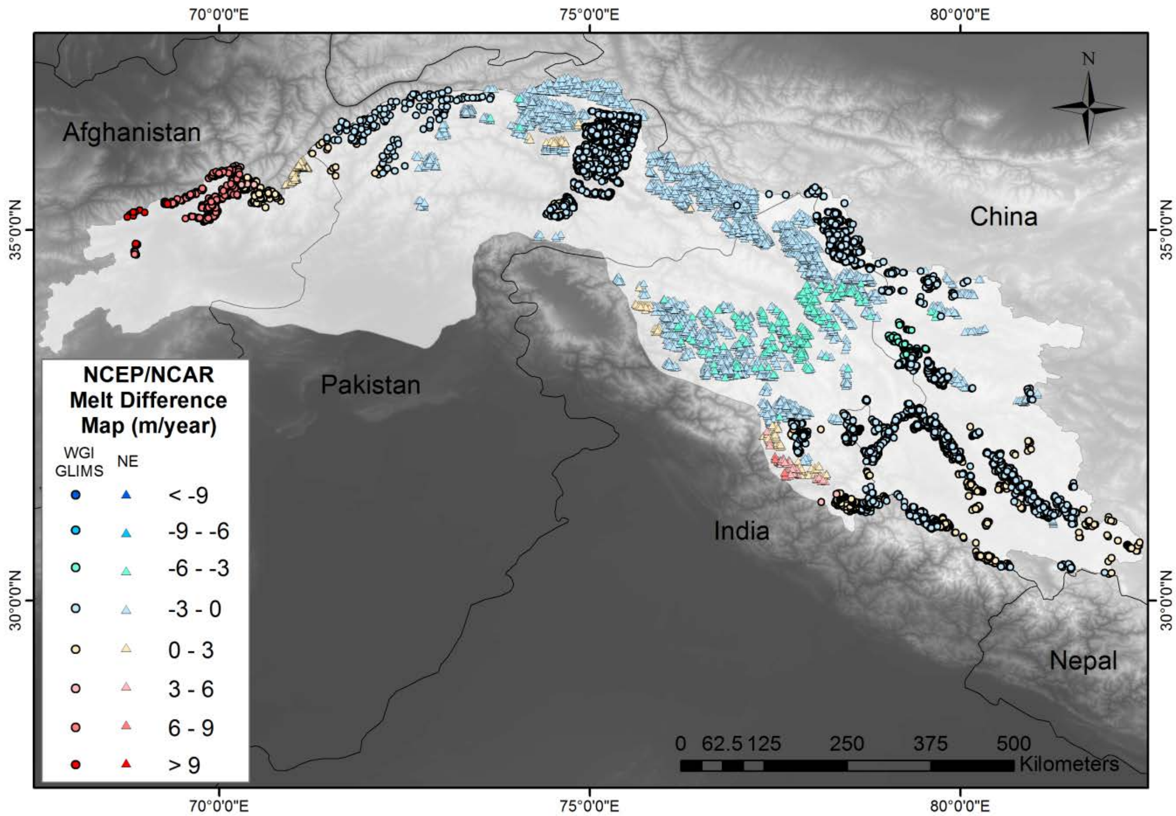

Figure 14: Map of melt difference for glaciers and glaciated areas using the control subtracted from the NCEP/NCAR reanalysis temperature data in meters per year. Circles represent WGI and GLIMS glaciers while triangles depict NE glaciated areas (2006; Kalnay *et al*., 1996).

5.6 Volume of Melt

The volume of melt is dependent on all the PDD model inputs. It is the first calculation to take into account the glacier surface area available to melt (equation 2). The correlation between glacier surface area and melt volume is higher than the correlation between melt volume and any other variable.

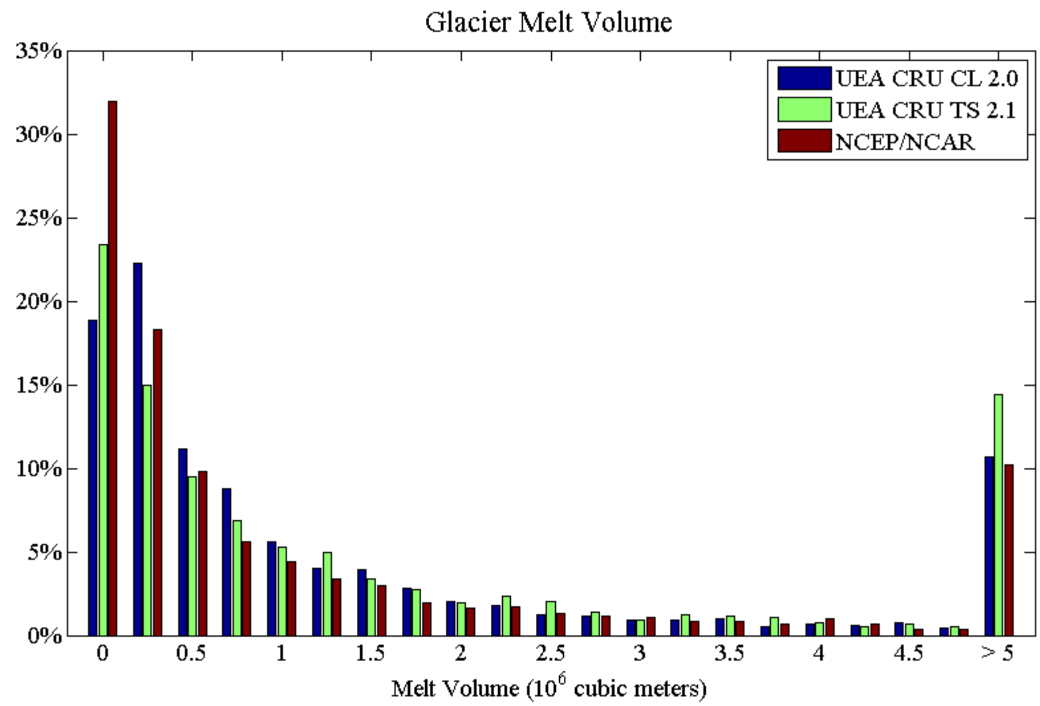

Figure 15: Histogram of glacier melt volume comparing the PDD model outputs for all climate datasets.

Table 11: Melt volume calculated for the maximum and minimum PDD model runs for all three climate datasets

	UEA CRU CL 2.0 (km^3)	**UEA CRU TS 2.1 (km^3)**	**NCEP/NCAR (km^3)**
Minimum Run			
Mean	0.006	0.007	0.004
Minimum	0	0	0
Maximum	0.364	0.372	0.234
Total	42.043	53.540	27.698
Maximum Run			
Mean	0.049	0.058	0.037
Minimum	0	0	0
Maximum	3.463	3.293	2.202
Total	367.480	438.550	276.330

5.6.1 Statistical and Spatial PDD Model output comparisons

Just as in the temperature and melt calculations, UEA CRU CL 2.0 was used as a control, and it was subtracted from each other melt volume output. Calculations compared the volume of melt by country and over the whole watershed. The regions with high average melt volume glaciers were predominantly in the northern and central regions of Pakistan and the southern portion of the watershed in India. This is expected because these glaciers experience high melt rates with this dataset, and the glacier surface areas available to melt are large. Numerically, the melt volume using this dataset ranges between 42 km^3 and 368 km^3 with an average of 165 km^3. This total average melt volume can also be numerically separated by country. Less than 1% was from glaciated area in Afghanistan, 3% in China, 50% in India, and the remaining 46% in Pakistan (Table 12). These percentages are relatable to the location of high melt volume glaciers in Figure 16. Of the three glacier datasets, 6% of the melt volume came from WGI, 5% came from GLIMS, and 89% came from NE glaciated areas (Table 12).

In addition to calculating the total melt volume from all glaciers, it is useful to know which glaciers are responsible for the majority of glacier meltwater calculated by the model. Using this dataset, more than 70% of the WGI and GLIMS melt volume over the watershed comes from 148 glaciers. Most of these high melt volume glaciers are located in Pakistan, but there are a few along the southeast and northeast edges of the glaciated watershed (Figure 17).

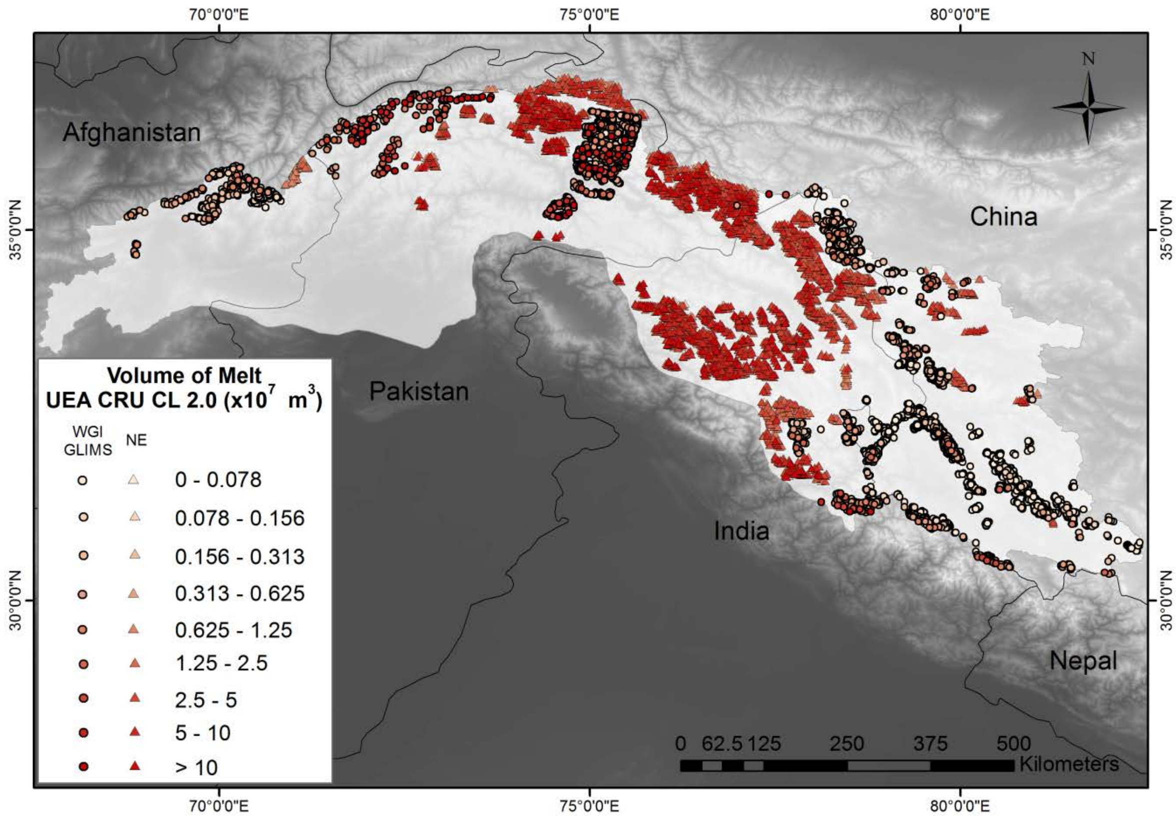

Figure 16: Map of mean melt volume derived using UEA CRU CL 2.0. Circles represent WGI and GLIMS while triangles depict NE (2006; Kalnay *et al.*, 1996).

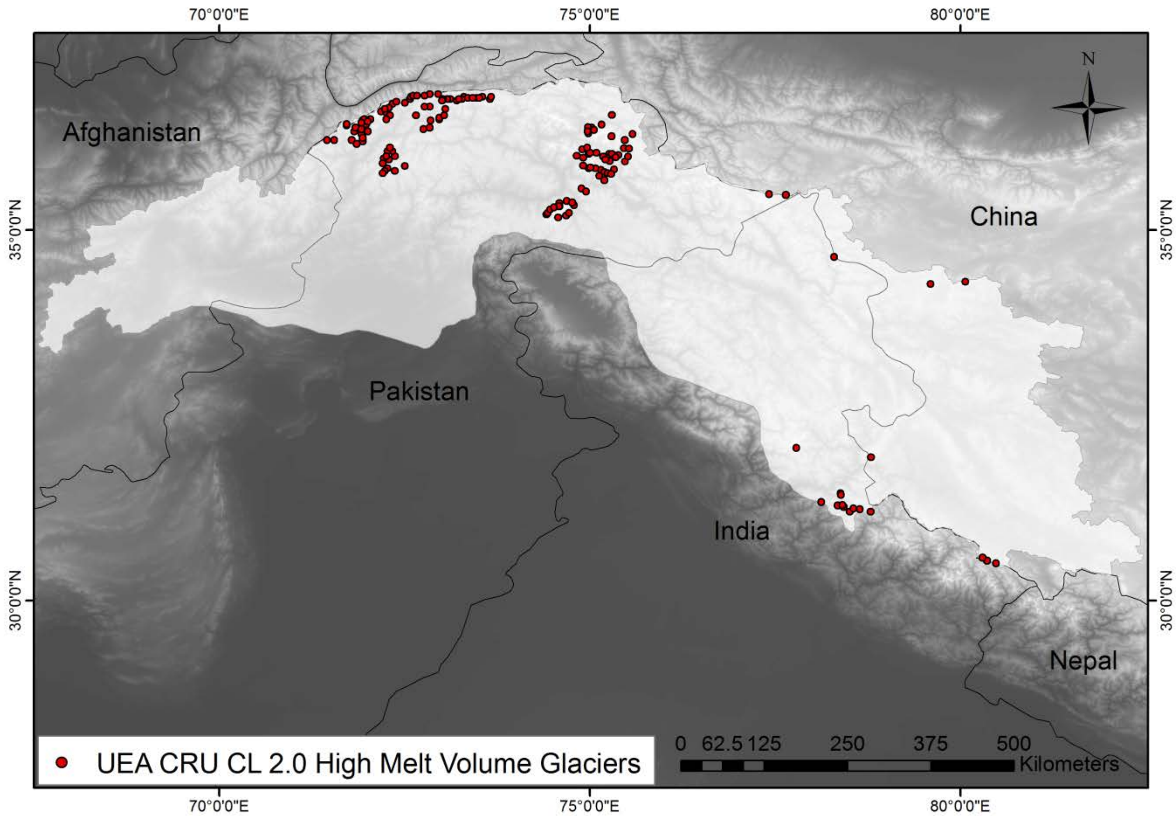

Figure 17: Map showing the 148 glaciers that contribute 70% of the total glacier melt volume when using UEA CRU CL 2.0. NE glaciated areas were not used in this calculation (2006; Kalnay *et al.*, 1996).

Spatially, UEA CRU TS 2.1 has higher melt volumes than the control in most of Afghanistan, northern Pakistan, throughout India, and western China (Figure 18). The largest positive differences are seen in northern Pakistan and the southern portion of the watershed in India. Glaciers with lower average melt volume than the control are found in small pockets throughout the watershed. This coincides with the spatial distribution of temperature and glacier area using UEA CRU TS 2.1. Glaciers with smaller surface area at cooler temperatures and higher elevations will produce less melt volume than glaciers with large surface areas at warmer temperatures and lower elevations. Numerically, the melt volume using this dataset ranges between 53 km^3 and 439 km^3 with an average of 315 km^3. These values are larger than the control, particularly in the maximum run. This is anticipated because glaciers and glaciated areas with greater melt rates should yield larger melt volumes when the area available to melt remains the same. Since area and temperature do not affect the PDD model linearly, the maximum run will experience the largest differences in melt volume outputs. Of the total mean melt volume, less than 1% was in Afghanistan, 6% was from China, 42% was from India, and 51% was from Pakistan (Table 12). Overall, this means each country experiences higher melt than the control using this dataset but to varying degrees. Of the three glacier datasets, UEA CRU TS 2.1 had 5% of the total melt volume calculated from the WGI glaciers, 3% from the GLIMS glaciers, and 92% from NE glaciated areas (Table 12).

Like with the control, it is important to understand which glaciers contribute the majority of total average melt volume. Since NE represents glaciated area and not individual glaciers, this dataset was excluded from this calculation. Using UEA CRU TS 2.1, 164 glaciers contribute to 70% of the WGI and GLIMS total melt volume. This included a few more glaciers than the control, but the glaciers contributing the majority of the melt using this dataset are predominantly in the same or similar locations as those in the control (Figure 19). Most of them are found throughout Pakistan and the northeast and southeast borders of the glaciated watershed.

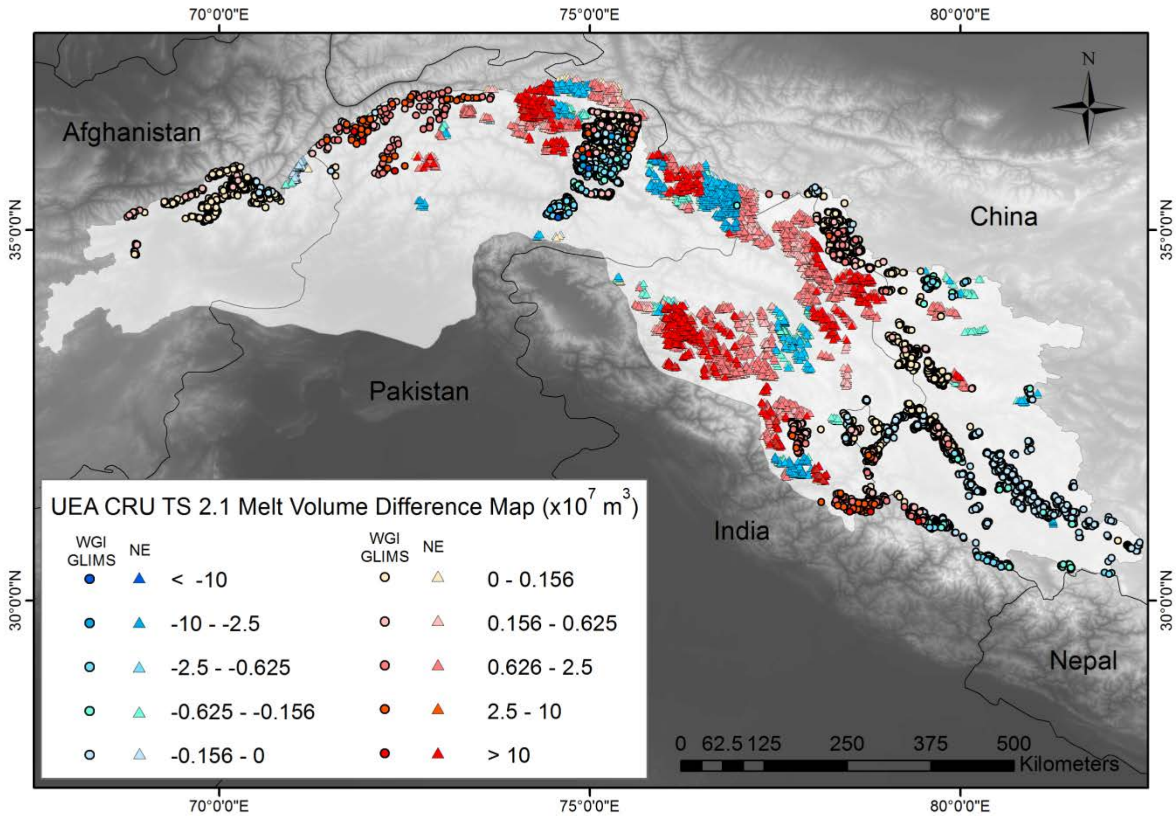

Figure 18: Map showing average difference in melt volume between UEA CRU TS 2.1 and the control. Circles represent WGI and GLIMS while triangles depict NE (2006; Kalnay *et al.*, 1996).

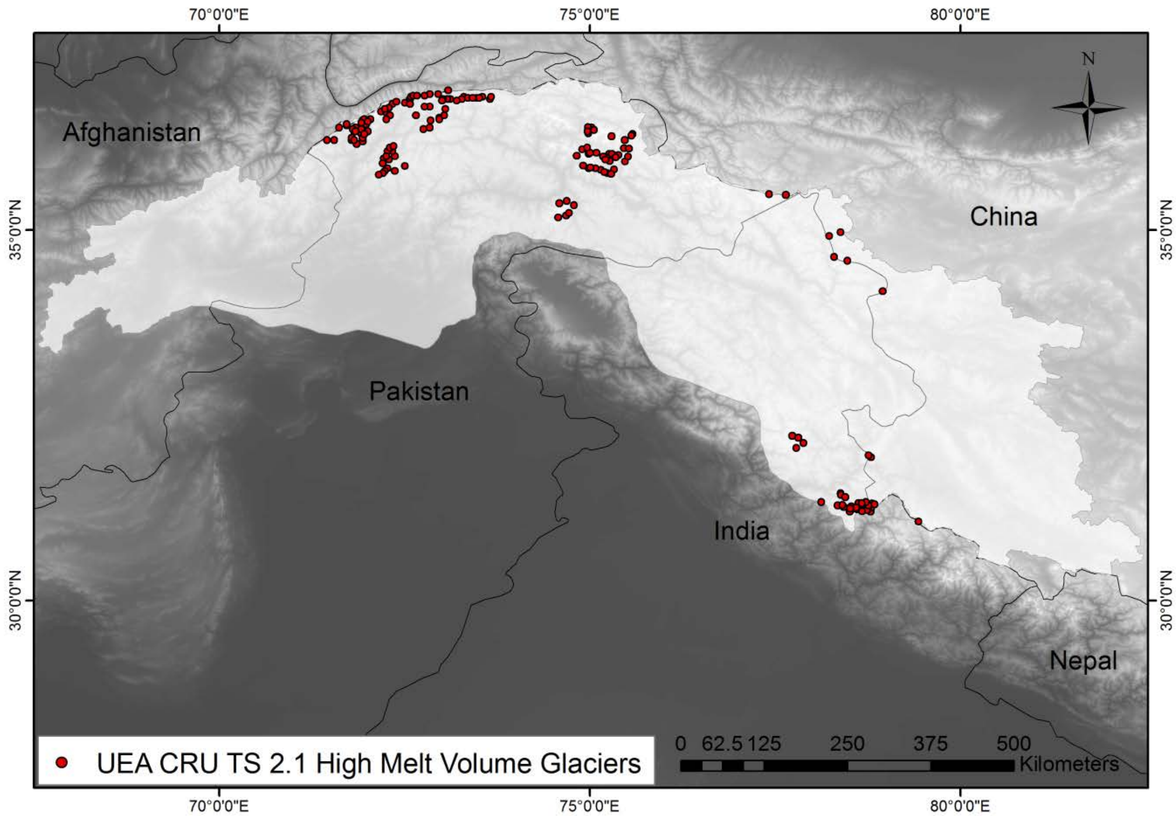

Figure 19: Map showing the 168 glaciers contributing 70% of the glacier melt volume when using UEA CRU TS 2.1. NE glaciated areas were not used in this calculation (2006; Kalnay *et al.*, 1996).

In contrast to UEA CRU TS 2.1, the glacier melt volume calculated using NCEP/NCAR at most glaciers is lower than the control. One exception involves the glaciers and glaciated areas in Afghanistan. This is also true of a few glaciers grouped at the southern edge of the watershed in India. Although there are a few other high melt volume glaciers, they tend to be spread around the watershed (Figure 20). Each of these differences coincides with differences in temperature. In most instances, this dataset yielded lower individual melt volumes than the control. With cooler temperatures yielding lower melt rates in most of the watershed, using the same surface area as the other datasets would result in lower melt volumes. Numerically, the melt volume using this dataset ranges between 27 km^3 and 277 km^3 with an average of 115 km^3.

Since many of the glaciers, especially those with large glacier surface areas, have lower temperatures and melt rates than the control, it is expected that the PDD model outputs would be lower. The majority of the glacier melt volume calculated from the PDD model looks similar to the control but with some noticeable differences. When analyzed by country, 2% of the melt volume came from Afghanistan, 3% from China, 45% from India, and 51% from Pakistan (Table 12). This equates to greater melt volume than the control run in Afghanistan, but less melt volume in all other countries. Since Pakistan generates the largest total melt volume, this still results in less total melt than the control. By glacier dataset, WGI accounts for 7%, GLIMS accounts for 5%, and NE glaciated area account for 88% (Table 12).

Determining which glaciers contribute the majority of melt volume using this dataset give the most unique results. 70% of the WGI and GLIMS glacier melt volume comes from 174 glaciers using this dataset (Figure 21). Many of these glaciers are found throughout Pakistan and along the southeast glaciated portion of the watershed like the control. The NCEP/NCAR data run also includes several high melt glaciers in Afghanistan, but these are a small percentage of the high melt volume glaciers.

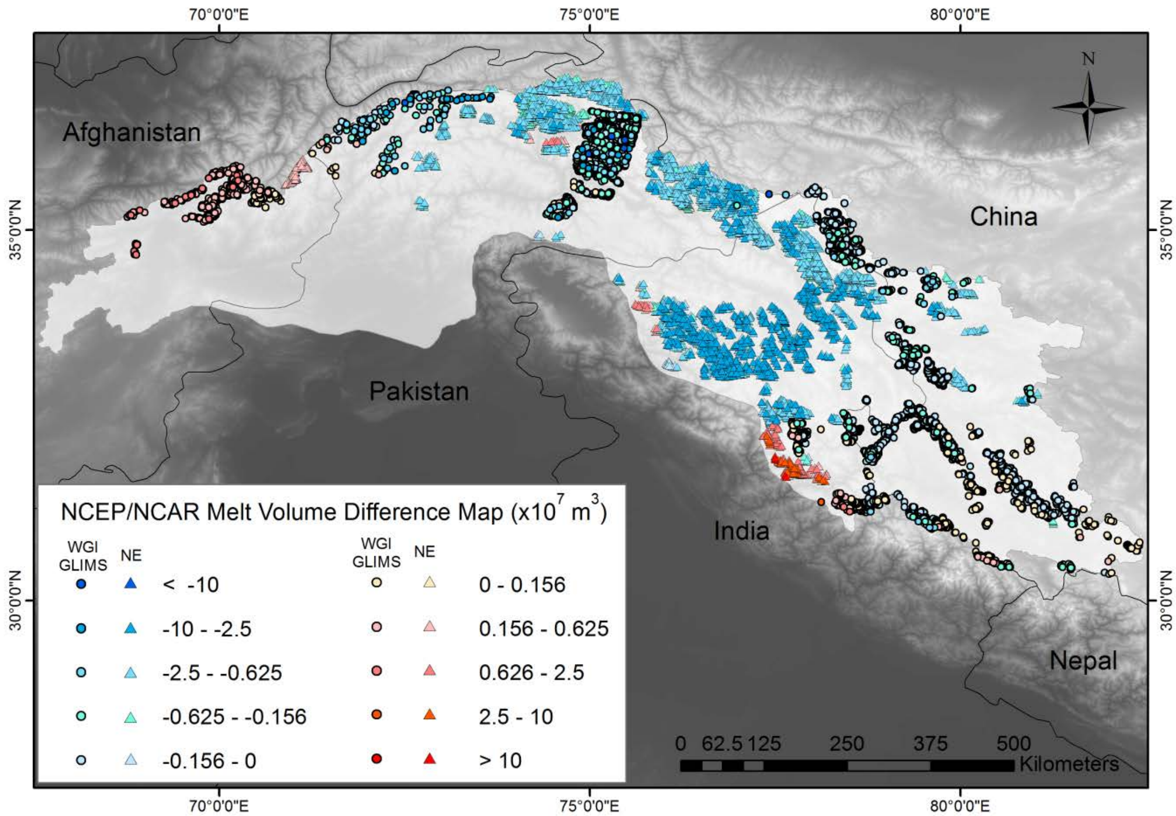

Figure 20: Map showing the average difference in melt volume between NCEP/NCAR reanalysis PDD model outputs and the control. Circles represent WGI and GLIMS while triangles depict NE (2006; Kalnay *et al.*, 1996).

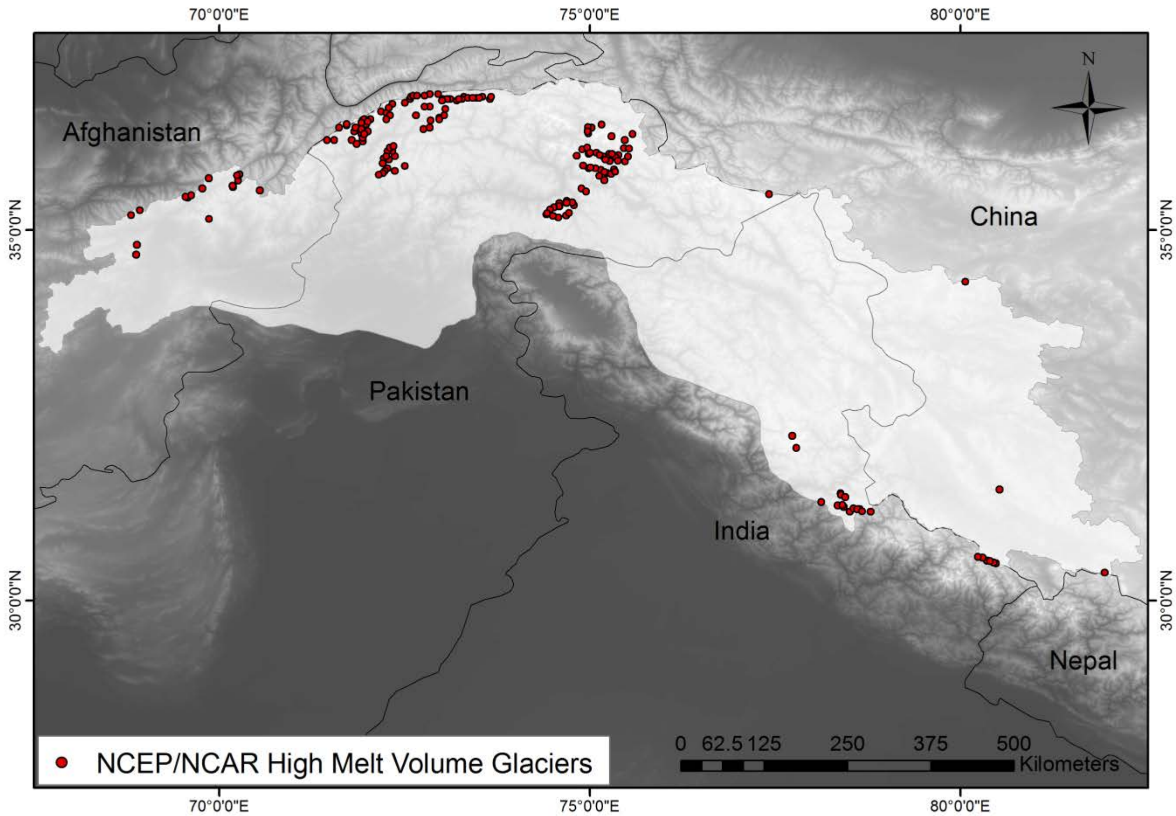

Figure 21: Map showing the 174 glaciers contributing 70% percent of the melt using NCEP/NCAR reanalysis. NE glaciated areas were not used in this calculation (2006; Kalnay *et al.*, 1996).

The above results provide bounds to the total melt volume coming from the Indus glaciers and locations of glaciers significant to it. The total melt volume is very likely between 27 km^3 and 439 km^3, the minimum NCEP/NCAR PDD model run and the maximum UEA CRU TS 2.1 PDD model run respectively. These two datasets provide end members for the melt volume calculations since temperatures in the NCEP/NCAR dataset are cooler than the control and temperatures in the UEA CRU TS 2.1 dataset are warmer than the control. Despite the range in melt volume and the differences in the temperature datasets, many of the glaciers identified as being the largest contributors to total melt volume come from the same regions. Glaciers in Pakistan have proven to be significant in all cases.

Table 12: Mean volume of calculated melt from glaciers separated by country, climate dataset, and glacier database. All values are in cubic meters unless otherwise specified.

Mean Volume of calculated melt from glaciers separated by country, climate dataset, and glacier dataset (m^3)

	UEA CRU CL 2.0					**NCEP/NCAR 2.5 degree**				
	WGI	*Glims*	*NE*	***Total***	***% of total***	*WGI*	*Glims*	*NE*	***Total***	***% of total***
Afghanistan	4.66E+08	1.70E+08	4.58E+08	1.09E+09	0.66%	1.14E+09	2.66E+08	6.24E+08	2.03E+09	1.76%
China	1.70E+09	5.30E+08	3.00E+09	5.23E+09	3.18%	1.16E+09	3.10E+08	1.42E+09	2.89E+09	2.51%
India	1.08E+09	1.32E+08	8.10E+10	8.22E+10	49.92%	1.09E+09	1.27E+08	5.06E+10	5.19E+10	45.02%
Pakistan	6.86E+09	7.42E+09	6.18E+10	7.61E+10	46.24%	5.14E+09	5.11E+09	4.81E+10	5.84E+10	50.70%
Total	1.01E+10	8.25E+09	1.46E+11	1.65E+11		8.53E+09	5.81E+09	1.01E+11	1.15E+11	
% of total	6.14%	5.01%	88.85%			7.41%	5.04%	87.55%		

	UEA CRU TS 2.1				
	WGI	*Glims*	*NE*	***Total***	***% of total***
Afghanistan	5.83E+08	1.93E+08	4.22E+08	1.21E+09	0.38%
China	2.52E+09	6.72E+08	3.51E+09	2.02E+10	6.42%
India	2.96E+09	4.67E+08	1.05E+11	1.34E+11	42.49%
Pakistan	9.00E+09	7.41E+09	7.03E+10	1.60E+11	50.71%
Total	1.51E+10	8.75E+09	2.91E+11	3.15E+11	
% of total	4.78%	2.78%	92.45%		

Table 13: Calculated correlation coefficient of mean melt volume outputs between datasets.

Correlation of glaciated area melt volume			
	UEA CRU CL 2.0	*NCEP/NCAR*	*UEA CRU TS 2.1*
UEA CRU CL 2.0	1.000	0.947	0.949
NCEP/NCAR	0.947	1.000	0.895
UEA CRU TS 2.1	0.949	0.895	1.000

5.6.2 Randomized Melt Volume Calculations

While the minimum and maximum PDD model runs provide bounds on the overall results, using a randomized scenario further shows how the melt volumes could vary due to differences in the melt factors, lapse rates, and area available to melt at individual glaciers.

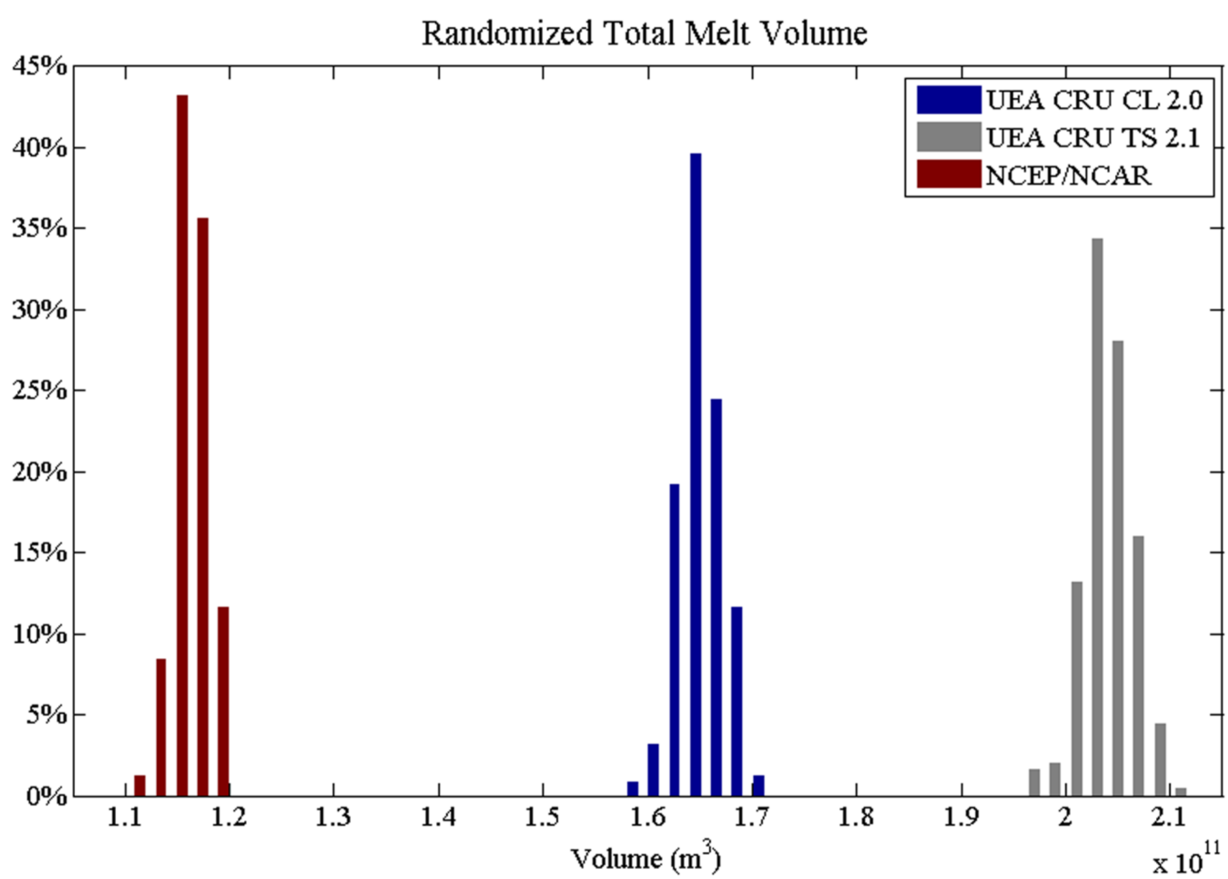

Figure 22: Randomized total average melt volume using all three glacier datasets. The control is bounded below by NCEP/NCAR and above by UEA CRU TS 2.1.

Using UEA CRU CL 2.0 the total melt from 250 randomized runs ranged from 160 km^3 to 170 km^3 with an average total of 166 km^3 (Figure 22). With UEA CRU TS 2.1, the total melt from 250 randomized runs ranged from 196 km^3 to 210 km^3 with an average of 204 km^3 (Figure 21). All of these values are larger than the outputs from the control. The total melt when the PDD model is applied to NCEP/NCAR from 250 randomized runs ranged from 111 km^3 to 120 km^3 with an average of 116 km^3 (Figure 21). Unlike UEA CRU CL 2.0 these values are all smaller than the control. As with the other PDD model scenarios, these total melt volume model outputs reflect the expected differences due to variations in temperature datasets.

5.7 Future Melt

In addition to understanding current melt outputs in the Indus watershed, it is important to predict how melt could vary due to future climate change. The IPCC has reviewed research which suggests climate change will result in different temperatures around the globe. To better understand the affect this may have on glaciers, this PDD model was applied to calculate glacier melt rate using three measurements of temperature increase above the original climate data: 0.5, 1, and 2 °C (Figure 23). The future temperature change estimations were applied to the UEA CRU CL 2.0 dataset only.

Table 14: Melt rate in m/year calculated assuming future regional temperature increases of 0.5 ºC to 2 °C

	Current Melt Rate	**0.5 °C increased T Melt rate**	**1 °C increase melt rate**	**2 °C increased melt rate**
Average	3.02	3.31	3.75	4.69
Minimum	0.00	0.00	0.00	0.00
Maximum	27.13	27.44	28.84	31.65

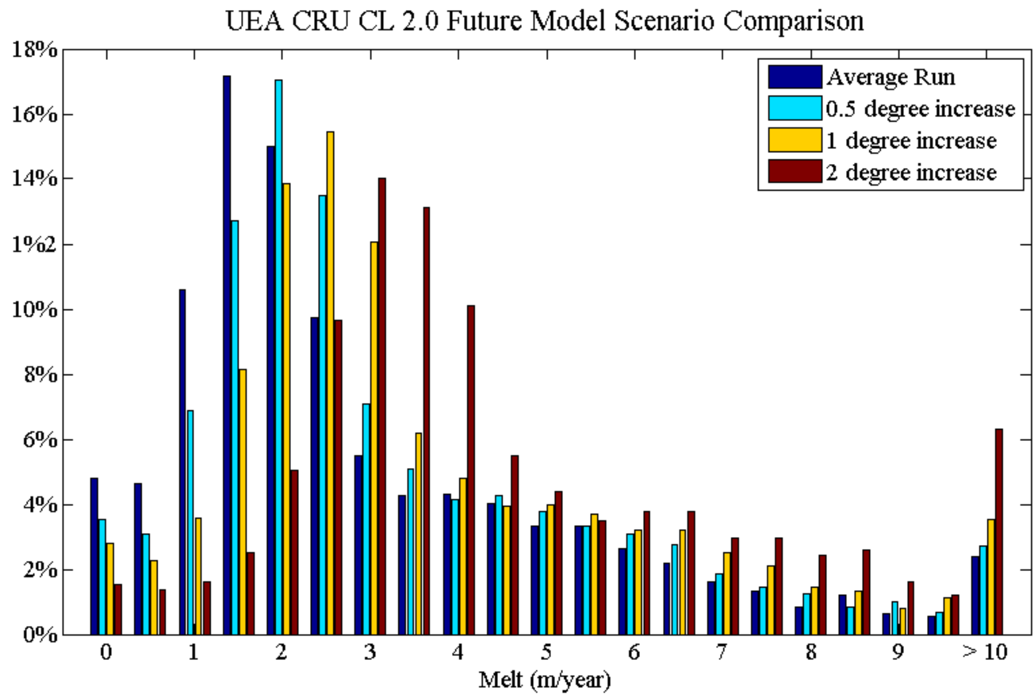

Figure 23: Histogram comparing all future melt scenarios. All values calculated in meters per year.

5.7.1: 0.5 °C

Applying a 0.5 °C increase to the WGI and GLIMS defined glaciers equally across the watershed resulted in an average melt of 3.31 m/year (Figure 24, Table 14). The values ranged between 0 and 27.44 m/year. Assuming surface area of the glacier changes little of relatively short time periods, a volume of melt can be calculated. With a universal 0.5 °C temperature increase across the watershed, this results in a melt volume of 243 km^3/year. This would increase the calculated melt volume from the control by 70 km^3.

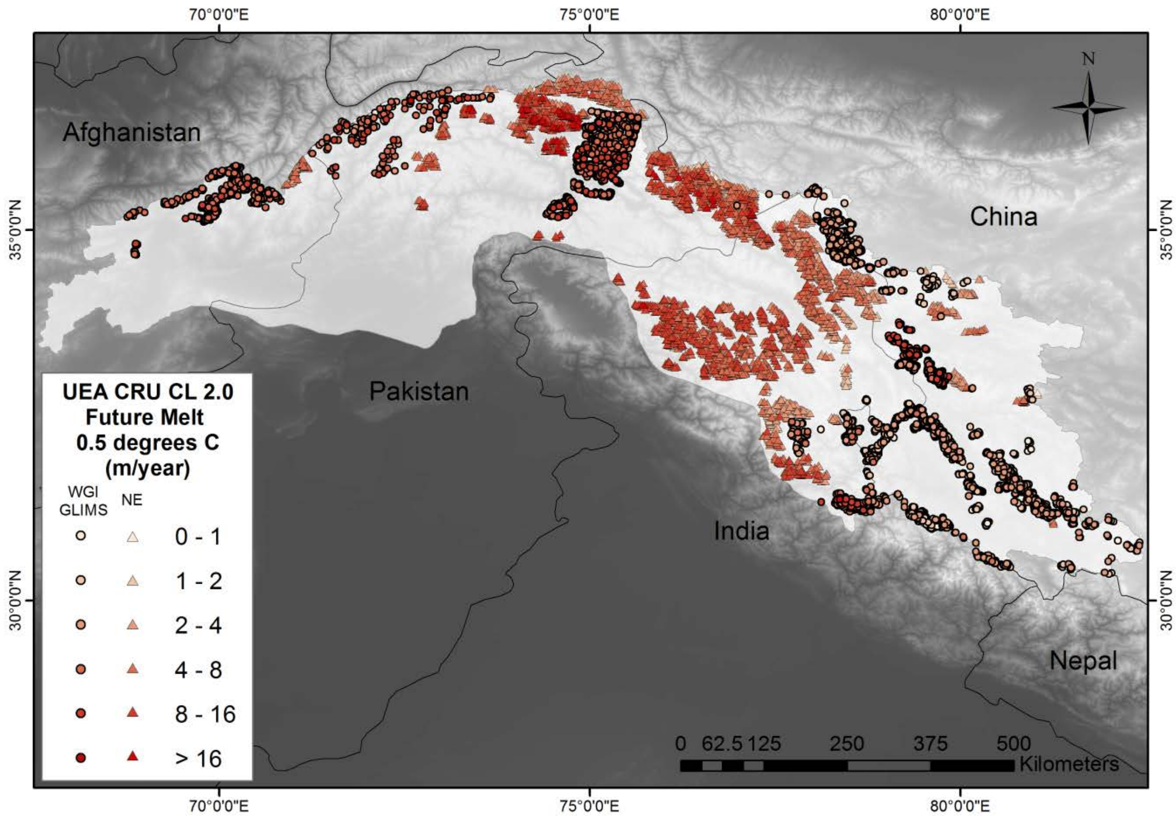

Figure 24: Map of potential future melt (m/year) assuming equal 0.5 ºC warming. These outputs utilize the control dataset only (2006; Kalnay *et al*., 1996).

5.7.2: 1 °C

As expected, a 1 °C increase in temperature applied equally across the watershed results in higher melt than both the control and the 0.5 °C increase (Figure 25). Average melt for all WGI and GLIMS glaciers using this climate input is 3.75 m/year with individual glacier melt varying between 0 and 28.84 m/year (Table 14). As above, it the surface area available to melt is assumed to be constant, a melt volume can be calculated utilizing a 1 °C temperature increase. This equates to a total melt volume of 258 km^3/year over the watershed, which is a 94 km^3 increase over the melt volume calculation for present day using the control.

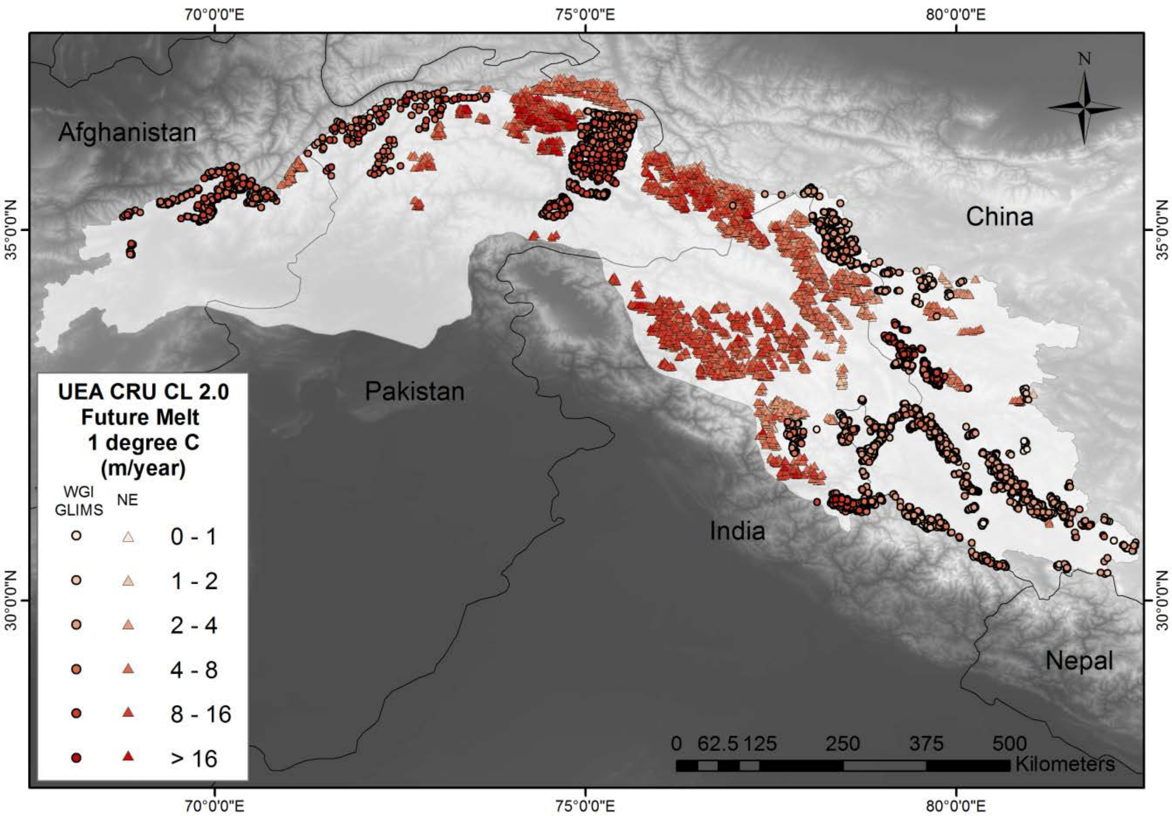

Figure 25: Map of future melt assuming 1 ºC warming over the watershed. These outputs utilize the control dataset only (2006; Kalnay *et al*., 1996).

5.7.3: 2 °C

The highest melt increases were seen due to a 2 °C increase in temperature of the UEA CRU CL 2.0 average values (Figure 26). This resulted in an average melt over the watershed of 4.69 m/year for WGI and GLIMS glaciers with a range of 0 to 31.65 m/year. That increases the average from the current temperature scenario by 1.67 m/year and the maximum by more than 4 m/year for individual glaciers (Table 14). While those numbers may appear small, between 1 and 4 additional meters of melt per year over a large glacier surface area would result in a significant quantity of overall glacier melt. Assuming the glacier surface area available to melt remains constant, this equates to 310 km^3/year which is 145 km^3 greater than the present day temperature calculations using the control. This means, a 2 °C increase in temperature over the watershed would almost double the melt volume output from glaciers in the region.

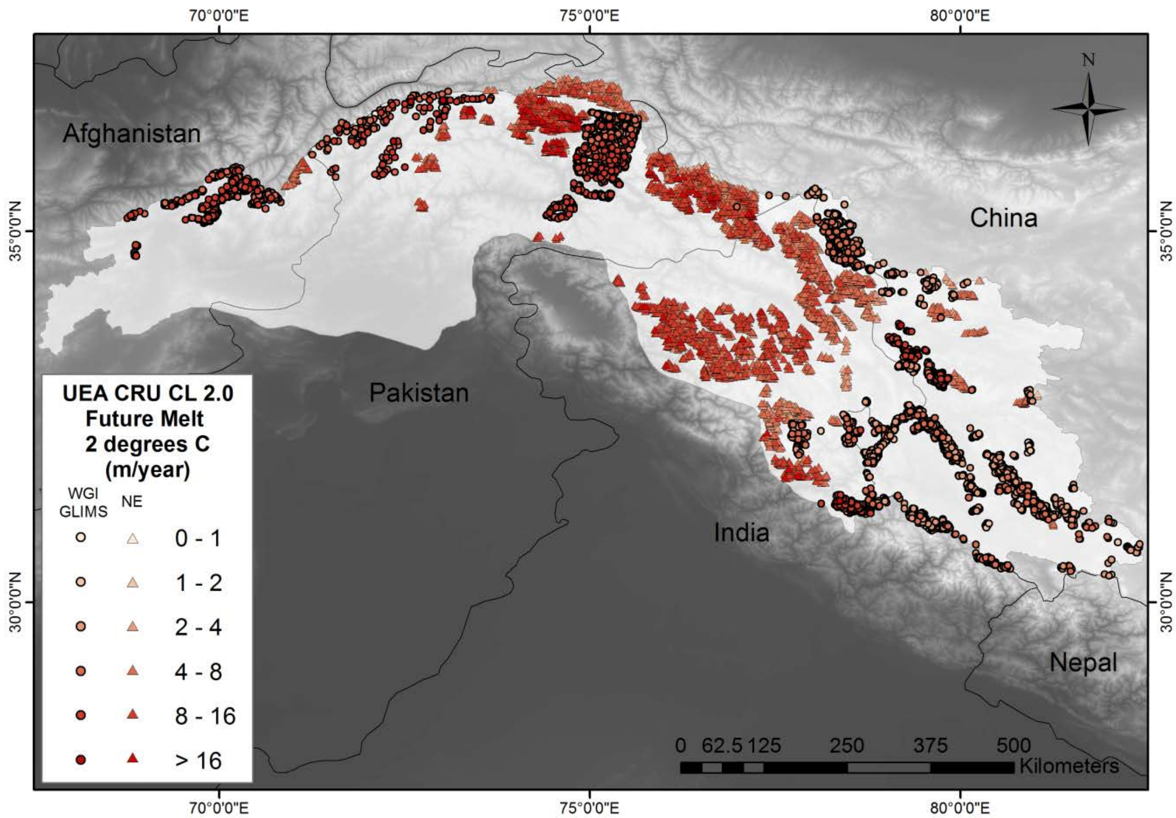

Figure 26: Map assuming 2 ºC melt over the watershed. These outputs utilize the control dataset only (2006; Kalnay *et al.*, 1996).

6. SUMMARY AND DISCUSSION

This study applied a PDD melt model to the Indus watershed, the results of which provide valuable information about regional patterns in glacier melt rates and volumes, as well as the uncertainties that attend PDD melt models when applied to larger spatial areas. The approach used in this study allows for a test of the sensitivity of glacier melt rates and volumes to uncertainties in climate datasets, glacier surface area, elevation, and melt factors. In particular, the location of glaciers relative to elevation and regional temperature lapse rates gives rise to the spatial pattern and magnitude of temperatures at each glacier. This then determines which glaciers are warmest and, therefore, have the highest melt rates. Although there are some spatial differences among the PDD model results depending on the climate dataset used, the spatial correlations between these different melt volume outputs are very high suggesting the overarching spatial pattern is similar from one climate dataset to the next. While the spatial pattern in melt volume is not very dependent upon the climate dataset used, the magnitude in melt volume is. However, the multiple combinations of climate datasets, melt factors, and uncertainty estimates used to generate a suite of modeled melt volumes provides bounds on the possible melt volumes across the region and likely captures the true volume of melt. Since the annual discharge of the Indus River is believed to be around 207 km^3/year, the melt volume output from glaciers is likely a large component (Economic Commission for Asia and the Far East, 1966). While the model does not account for melt water loss from the Indus River before the discharge was calculated, the model outputs are still large in comparison to the total river discharge. Therefore, all model runs indicate glacier melt is an important source of water in the Indus River watershed.

6.1 Melt Rates and Volumes

Each of the three climate datasets used as input in the PDD melt model (UEA CRU TS 0.5 (the control), UEA CRU TS 2.1, and NCEP/NCAR) offered unique results about the potential glacier melt volume in the watershed. However, the results of all three calculated melt volumes are within the same order of magnitude, and all have very similar spatial patterns. Indeed, the spatial correlation of melt volume outputs between runs using the control and the other climate datasets is r~0.95. As expected, melt rates in the watershed are greater in areas with glaciers at warmer than average temperatures. The vast majority of these are located in northern Afghanistan and Pakistan as well as the southern portion of the glaciated watershed in India. Since the volume of melt is highly affected by the area of glaciers available to melt, it is largest where there are both high melt rates and large areas of glacial ice. Because of this, melt volume is greatest for glaciers and glaciated areas in the north and central regions of the watershed in Pakistan and the south and central Indian glaciated watershed. Melt volume is less in places where temperature, glacier size, or both are relatively small. This is evident in much of China's portion of the watershed as well as northernmost India. The number of glaciers contributing the majority of melt is also very similar for each climate model run. In each case less than 5% of glaciers contribute more than 70% of the total melt volume. Although there are spatial differences in the location of high melt volume glaciers between the three datasets, there is a significant amount of overlap. All calculations suggest many glaciers in Pakistan in particular are important contributors to total melt volume (Figures 17, 19, and 21). Further study of these glaciers with a focus on ground-truthing temperature and glacier surface area measurements could be invaluable to better understanding water resources in the Indus watershed. Defining individual glacier extents in regions where only glaciated area information is provided would also be beneficial for refining the pattern of glacier melt volume.

6.2 Model Variation and Uncertainty

As discussed above, temperature will affect both the magnitude and spatial patterns in melt volume across the watershed. However, melt volume will also depend on the assumed melt factors and area of the glacier over which melt occurs. To quantify the uncertainty in melt volume calculations due to uncertainties in temperature at the glaciers, melt factors, and melt area, four scenarios were modeled: mean melt (discussed above), maximum melt, minimum melt, and randomized distribution of uncertainties. Each scenario was run for the three climate datasets for a total of 12 melt volume calculations. This allows for a test of the sensitivity of the results to temperature, melt factor, and ablation area.

6.2.1 Temperature Variation and Uncertainty

The spatial differences when comparing PDD model results using different climate datasets help show where the model has uncertainty due to temperature. The highest positive melt differences between UEA CRU TS 2.1 and the control were seen in the southern Indian portion of the glaciated watershed and over a few small glaciated areas in northern Pakistan. The NCEP/NCAR reanalysis also resulted in spatial differences from the control. While it generally resulted in smaller melt rates and volumes than the control, exceptions are in Afghanistan and the southern portion of the glaciated watershed in India.

In addition to spatial variability, using different climate datasets in the PDD model leads to different overall magnitudes of melt volume. Since using UEA CRU TS 2.1 climate data results in a larger number of large, high temperature glaciers, it results in the highest melt volumes. The converse is true for NCEP/NCAR reanalysis model outputs.

These small spatial and magnitude differences could arise from several combining factors that may include differences in model formulations, time periods of data analysis, spatial scales, and source data. First, the model formulations refer to how temperature is calculated for each model. Both UEA CRU climate datasets were determined by interpolating weather station data using a numerical model to account for varying station distribution. NCEP/NCAR reanalysis calculates the temperature using an analysis and forecasting system of interpolated data. Second, these climate datasets had unique timespans over which their data was collected. This could result in different PDDs between datasets if some contained information from more warmer or cooler years than others. However, since the time spans each cover at least 29 years, it is expected this would largely average out. Future research should be done to determine actual temperatures in locations throughout the watershed to compare to each temperature dataset. Third, these datasets were constructed over different spatial scales ranging from 10 minutes to 2.5 degrees. This results in varying resolutions to capture temperature over the same spatial extent. This is also affected by the lapse rates since temperature at individual glaciers has not been directly measured throughout the watershed. The lapse rates were calculated using a 2.5 degree grid cell like the NCEP/NCAR climate data. Due to this, they do not coincide perfectly with the expected change in temperature with elevation the UEA CRU climate datasets would predict. This would result in uniform lapse rates being used over larger areas than would necessarily be reality. Furthermore, as the climate grid becomes more coarse, it likely increases the difference between the actual topographic elevation and the elevation of the glaciers or glaciated areas. This difference would result in greater application of the lapse rates which could create pockets of larger temperature, melt, and volume difference relative to adjacent locations and could explain some of the spatial variability seen in the dataset comparisons. Lastly, the climate data came from different sources. Both UEA CRU climate datasets were determined using weather station data while NCEP/NCAR reanalysis uses a larger variety of temperature data.

6.2.2 Melt Factor Uncertainty

Unlike temperature, melt factors used in this PDD model would only affect the magnitude of the mean, maximum, and minimum model outputs because one melt factor was used over the watershed. Since the melt factor signifies the expected amount of melt for a given PDD, errors in it could affect the melt volume outputs of the PDD model. Higher melt factors cause greater melt volumes while lower melt factors create smaller melt volumes. While regional melt factors averaged from glaciers throughout Asia could be representative of most glaciers, there could be notable exceptions. Since the majority of glacier melt appears to be coming from a relatively small percentage of glaciers in the watershed, melt factors should be determined for these glaciers. These could be compared to the melt factors used in this study to determine errors associated with this more generalized approach. While the randomized, minimum, and maximum PDD model scenarios account for some differences in melt factors, the model is unable to account for changes at individual glaciers due to aspect, shading, or other regional factors. These model scenarios, therefore, do not take into account spatial patterns in melt volume due to potential spatial patterns in melt factors.

6.2.3 Area Uncertainty

Like melt factors, glacier area available to melt impacts the magnitude of melt volume using the PDD melt model for the mean, minimum, and maximum model runs. Larger (smaller) surface area values cause greater (smaller) melt volumes. Uncertainty in these surface area values could result from the age of the glacier datasets. The information in the WGI and GLIMS databases was collected over a large time scale (Table 5). Since the aerial photographs were taken these glaciers may have changed in size. This would especially be true of glacier surface areas determined from photographs taken in the early part of the 20th century, but likely also affects all glaciers to some degree. Changes in glacier area would result in a different melt volume calculated for both individual glaciers as well as over the entire watershed. However, this uncertainty is addressed to some degree in the minimum, maximum, and randomized PDD model scenarios by including an error uncertainty in glacier size estimates and the percent of area over which melt is assumed to occur (Figure 2).

7. CONCLUSIONS

Overall, by using this model much has been accomplished so far to better understand the quantity of glacier melt in the Indus watershed. Although each temperature dataset yields different values for temperature, melt, and melt volume, the overall total volumes of melt are within the same order of magnitude and show very similar spatial patterns. This suggests the model, and its accompanying scenarios, has captured the true value of melt, between 27 km^3 and 439 km^3. Furthermore, this study shows that a small percentage of glaciers (less than 5%) contributes more than 70% of the total melt volume. Despite some spatial differences in temperature between climate datasets, calculations suggest larger glaciers across Pakistan may be particularly important to melt volume contributions for the Indus River. Since glacier surface area has the largest influence on the melt volume calculations, over time the area values are likely to have a far greater influence on melt volume than changes in temperature. Further research should be done to determine the total number of glaciers in the watershed, update the surface area of present glaciers, and increase the certainty in temperature at these glacier locations. In addition, this study demonstrates the sensitivity of future melt volume calculations to small changes in temperature. Continued research into Asian climate change will provide the information needed to better calculate the future melt volume of glaciers in the region. In addition, this PDD model should be applied to other regions around the globe to determine whether the model produces spatially consistent results in other locations.

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