



## AN ABSTRACT OF THE THESIS OF

Quin Ourada for the degree of Master of Science in Geography presented on March 20, 2009.

Title: Using Reanalysis Data to Characterize Arctic and Sub-Arctic Glaciers

Abstract approved:

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The net mass balance fluctuations of Arctic and Sub-Arctic glaciers, north of 47.5° North latitude, are described over a 45-year period from 1957 to 2002 using two parameters derived from a gridded climatology reanalysis. Variability among 185 measured glaciers was represented according to two main components. The first component represents the temporal variability of the net balance series derived from a statistically defined geographic region. The second component represents the glacier-specific variability in the net balance series (the amplitude of variability). Each component was numerically derived using gridded monthly mean temperature and precipitation data at a 2.5° spatial resolution. These two main components of the net balance series can be determined from simple glacier location data. The temporal variability component was determined using patterns of warm season temperature that were then used to define the statistically correlated regions. The glacier-specific component was approximated along continuum of continentality. Continentality was based on the relative ratio of warm to cool season temperature at the glacier location, which was then normalized and differenced using precipitation magnitude.

Ultimately 21 distinct geographic regions containing at least one representative glacier were defined for the first, temporal component. In data-rich regions, such as the Alps

and Scandinavia, spatial variability was identified on a finer scale than individual mountain ranges. The temporal evolution of measured net balance series within each region were more closely related to each other than measured mass balance on the scale of mountain ranges. This temporal signal can be considered the most likely temporal signal that would be characteristic of unmeasured glaciers within the spatial extent of the region. This spatial extent defined for each region is specific, and based on similarities in physical climatology as opposed to more vaguely defined regions based on mountain ranges or other geographic features. The, second, glacier specific component of the series was related to net balance standard deviations (58% variance explained), balance amplitude (55% variance explained) and climate sensitivity (56% variance of temperature sensitivity and 52% variance of precipitation sensitivity explained) for measured glaciers. The normalization process resulted in a glacier continuum ranging from -1 to 1 to describe the relative position of a glacier along a continuum or wet-maritime to dry continental.

These two pieces of information can be used together to approximate a large component of the net balance series for an unmeasured glacier based on location alone. Representing unmeasured glaciers in this manner is, by no means, a substitute for actual field measurements or complex and highly parameterized mass balance models. This approach is also limited in accuracy by the spatial resolution of the gridded climatologies used, which at this time are still quite coarse,  $2.5^\circ$ . However, in lieu of more detailed data, a simple approximation of glacier mass balance can be made and those measured glaciers most likely to exhibit similar characteristics can be identified to assist in tuning parameters for a more detailed mass balance model.

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Using Reanalysis Data to Characterize Arctic and Sub-Arctic Glaciers

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Quin Ourada, Author

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## **CHAPTER 1 – INTRODUCTION**

Understanding the complex role of small glaciers and ice caps in global hydrologic systems has been the subject of intense study, especially in the later half of the 20th century. Characterizing the relationship between perennial ice masses and climate is an important key to understanding the important role of glaciers in this system.

Global ice masses store tremendous quantities of fresh water. Glacier extent is the result of climates, past and present and serve as a constant reminder of the dynamic nature of the earth system. At a time when awareness of climate impacts to daily activities is at an all time high, it is imperative we understand major controls of these systems, yet our ability to study glaciers directly is seriously limited by our ability to access these generally isolated systems. So an effort to characterize the full range of glacier systems depends on our ability to adequately represent the behavior of glaciers that have been studied relative to those glaciers that have not been studied.

The very nature of the glacier defies basic representation. Each ice mass is an individual, and in the case of large ice caps or ice sheets, such as Greenland or Antarctica, the individual ice mass is comprised of a complex array of systems acting both individually and as part of a group. Something as simple as understanding where one individual ends and another begins can be difficult. Glaciers are dynamic, the glacial environment is dynamic, glacier composition itself is dynamic. Even with our present and vast computational powers, it is not yet possible to produce a model that can reliably describe the complex nature of a large quantity of glaciers. In order to asses the present status of those glaciers lacking direct observation requires

interpolation, extrapolation and scaling of information learned from relatively small population glaciers that have been directly studied. To begin to understand glaciers beyond the scale of the individual ice mass it is imperative to find mechanisms that can relate glaciers within a region.

For this work the definition of a glacier is limited to “small glaciers and ice caps” following Dyurgerov and Meier (2005). This describes all perennial ice masses with the exception of the large ice sheets of Greenland and Antarctica or the outlet glaciers of these large ice sheets. This definition is pervasive in the literature and is also referred to as alpine glaciers and ice caps. The World Glacier Inventory (WGI) estimates there are about 160,000 small glaciers and ice caps. These glaciers are particularly important to the present climate system due to a high climatic sensitivity and high mass turnover rate (Oerlemans, et al., 1998). Sea level rise attributed to small glaciers and ice caps was roughly 12 to 22 cm in the 20<sup>th</sup> century (Bindoff et al., 2007; IPCC, 2007). Independent evaluations of glacier mass loss and climate warming over the Arctic have confirmed the correlation between glacier mass loss and climatic warming since 1960 (e.g. Cogley and Adams, 1998; Meier et al., 2007). Over a time period from 1961 to 1997 small glaciers lost an estimated total of  $3.7 \times 10^3 \text{ km}^3$  of water equivalent (Dyurgerov and Meier, 2000). Utilizing the fairly limited set of data available from directly measured glaciers to represent all unmeasured world glaciers is a process that may be significantly flawed (Dyurgerov and Meier, 2000; 2005; Hock, 2005; Greene, 2005; Oerlemans, et al., 2005). However, this process is how estimates of global glacier response to climate, and global estimates of glacier

contributions to the hydrologic system have been derived. These and similar efforts to accurately represent the system are the subject of much current research.

The vast majority of the 160,000 global ice masses have not been directly measured. It is imperative to understand what factors are most useful in describing glacier response to climate. Moreover, one must use the most important variables comprising glacier response to climate to represent the spectrum of that response in a basic manner. Doing so will assure that representation of the response of unmeasured glacier is derived using the best surrogate measured, or “reference”, glacier.

Parameters used to represent these unmeasured glaciers can then be tuned, where data allows, using this most appropriate reference glaciers. Ultimately these tuned parameters can be used as a basis for logical scaling to the appropriate area of unmeasured ice. The creation of a representation scheme that considers a system with such complex spatial and temporal patterns can seem daunting (Braithwaite, 2009; Dyurgerov and Meier, 2005), however a number of significant steps toward this end have been reasonably successful (Braithwaite and Zhang, 1999; de Woul and Hock, 2005; Letreguilly and Reynaud, 1989; 1990; Meier, 1984; Oerlemans et al., 2005). Toward this end, this project addresses two specific objectives.

1. To define spatial regions within which a temporally homogeneous mass balance signal can be identified.
2. To characterize the degree of continentality to represent the glacier specific component of the mass balance signal. Continentality refers to the degree to which a glacier is removed from a precipitation producing humidity source.

Addressing these objectives should lead to the climatic characterization of the most important components of the net mass balance of measured and unmeasured glaciers utilizing the spatial and temporal patterns of simple climatic data. From this characterization the most appropriate measured glaciers can be identified to assist in accurate representation of the mass balance signal from the unmeasured glacier.



## CHAPTER 2 – REVIEW OF PREVIOUS WORK

### 2.1 History

The simplest methods for modeling glacier mass balance from climate data involve regression models that tune a mass balance series to temperature and precipitation from a nearby climate station. Distributed models, such as the degree-day model, utilize a full series of mass balance data distributed over the entire surface of the glacier. These distributed models have become very popular for identifying glacier sensitivity to a standard +1°C temperature change (de Woul and Hock, 2005; Oerlemans et al., 2005; Tarasov and Peltier, 1997). A more detailed approach for identifying glacier specific sensitivity would be an energy balance model. Highly parameterized energy balance models have been accurately implemented on a number of glaciers (Braithwaite and Zhang, 1999; Oerlemans, 1992). Unfortunately energy balance models and distributed degree-day models require a nearby climate stations to obtain the input data for each of the many parameters (Hock, 2005). The necessary input data are not available at the location of many glaciers (Cogley and Adams, 1998). To this end we step back from these complex modeling efforts, which are generally carried out over individual or small groups of glaciers at small scales, and look toward methods that can make good use of the information obtained from these detailed modeling efforts at a regional scale.

Historically a number of regional modeling approaches have been used to address the question of the role of small glaciers and ice caps in the hydrologic system. Meier (1984) identified a method to scale balance amplitude, and mean balance to 13

regions, thereby identifying a rise in sea level of  $0.46 \pm 0.26 \text{ mm yr}^{-1}$  for the period 1900 to 1961. Dyurgerov and Meier (1997b) similarly identified recent small glacier and ice cap annual contribution to sea-level rise of  $0.25 \text{ mm yr}^{-1}$  but found contribution accelerated in the mid 1980s. Meier and Bahr (1996) used scaling relationships to find regional distributions of surface area, volume and thickness reporting a total glaciated area of  $0.68 \cdot 10^6 \text{ km}^2$  and a volume of  $0.18 \pm 0.04 \cdot 10^6 \text{ km}^3$  comprising a total sea-level equivalent of  $0.5 \text{ m} \pm 0.10 \text{ m}$ . Cogley and Adams (1998) noted a thickness loss increasing from near 0 in the 1960s to about  $0.3 \text{ m yr}^{-1}$  from 1980 to 1990. Other simplified methods aimed more toward calculating an average global sensitivity have been attempted. Raper and Braithwaite (2005) use a gridded approach, determining the component of each grid covered by ice caps and small glaciers outside of Greenland and Antarctica to estimate a total ice volume of  $0.087 \pm 0.010 \cdot 10^6 \text{ km}^3$  and a smaller total potential sea-level rise equivalent of  $0.24 \pm 0.026 \text{ m}$ . Bahr and others (1997) use numeric scaling methods to derive an empirical relationship for glacier area distributions. Oerlemans et al., (2005) calculated a representative seasonal sensitivity characteristic for 13 different regions to calculate changes in the surface balance of individual glaciers. Ohmura (2004) estimated a total, global ice volume of  $33.1 \cdot 10^6 \text{ km}^3$  and a volume of mountain glaciers of  $0.056 \cdot 10^6 \text{ km}^3$ . These volumes are used with detailed winter and summer balances to calculate an average mass balance from 75 long-term mass balance time series of  $-270$  to  $-280 \text{ mm yr}^{-1}$  and a discharge rate of  $140 \text{ km}^3 \text{ yr}^{-1}$  or  $0.4 \text{ mm yr}^{-1}$  sea level equivalent for the second half of the 20<sup>th</sup> century (Ohmura, 2006). Winter and summer balances are used to determine the exact cause

of the net negative balance over this time period (Ohmura, 2006). Greene (2005) also identified a hemispherically-averaged balance series using winter, summer and net balance averages. A number of these approaches suggest a glacier thickness loss of a few decimeters per year, and differ by less than  $0.1 \text{ m yr}^{-1}$  (Haeberli et al., 1999). Considering the quantity of unrepresented ice and the variety of different variables, parameters and proxies used to scale to larger areas and regions, this level of consistency among methods is impressive.

## **2.2 Justification**

Each of these previously mentioned methods approaches the problem of aggregating glaciers into regions for homogenous treatment using a variety of methods (Table 1). Some authors created gridded surfaces, others used climatically homogeneous regions, geographic regions, or just mountain ranges. The spatial distribution of glaciers is irregular and the method in which glaciers are grouped impacts the results of extrapolation studies. Braithwaite (2009) suggests “We urgently need to find better ways of analysing sparse datasets with ‘complex spatial and temporal patterns’ like the present mass balance dataset.” However, there is broad general agreement in the results of a number of different studies. Agreement has often been attributed to the large quantity of unknowns that essentially cancel each other out (e.g. Ohmura, 2006). It may be true that unknowns will cancel each other out, but this non-standard treatment of the spatial distribution of glaciers makes cross comparison of the results of the individual studies and identification of a thoroughly and consistently defined region difficult.

Additionally few measured input parameters are easily identifiable, treated consistently or readily available for application to an unknown glacier (Haeberli et al., 1999). There is a need for a repeatable, generally accepted, numeric approach to glacier representation. A system that defines geographic regions by climatic setting would allow parameters to be defined and appropriately valued by location alone, without requiring direct measurement. Such a system would assist the needs of the WGI and help future researchers, scientists and the public at large to better understand the geographic distributions of the specific extrapolation and scaling methods that are frequently employed. This would also help facilitate comprehension of the vast body of knowledge that has been extracted through the many judicious treatments of the precious, but significantly limited quantity, of directly collected mass balance data. To this end a basic system of glacier representation to characterize the main identifiable traits, or principle components, of a glacier is proposed.

**Table 1 A sampling of different approaches to glacier aggregation to regions**

<b>Author</b>	<b>Regions</b>	<b>Basis</b>
Haeberli et al., 2000	20	Mountain Range
Hoelzle et al., 2003	5,8	Length, Mt Range
Ohmura, 2004	14	Geographic/Mt. Range
Letreguilly & Reynaud, 1990	4	Continental
Dyrurgerov & Meier, 1999	28	Climatic regime
Meier, 1984	31	Climatic regime
Braithwaite, 2002	13	Sub-Continental
Haeberli, 1998	31	Climatic regime
Raper & Braithwaite, 2005	7	Geographic/Mt. Range
Oerlemans et al., 2005	10	Climate regime

For a complete glacier inventory Haeberli (1998) suggested the following descriptive parameters be used: glacier length, maximum and minimum altitude, and glacier surface area. A general basis for representation should be designed such that it can be enhanced by ongoing collection of valuable direct measurements. The quantitative representation of related changes in glacier length, mass balance and climate for unmeasured glaciers will come from the limited mass balance measurements in different climatic regions (Haeberli, 1998). Following this logic we identify the need for a quantitative definition of standard regions, defined by climate regime, from which representative glaciers can be identified. Despite the unique nature of individual glaciers, they are clearly limited in range by a specific set of climatic conditions that must be present. The intention is to recognize the principle variants

within those specific conditions and represent the geographic distribution of the common climate parameters that pertain most important components of glacier mass balance variation. As shown in Figure 1, the goal of climatic representation of glacier mass balance follows the concept that variations in the mass balance series of individual glaciers can be largely explained by the first two main components, a regional temporal signal and a glacier specific physical signal (Letreguilly and Reynaud, 1989; 1990)Figure 1.

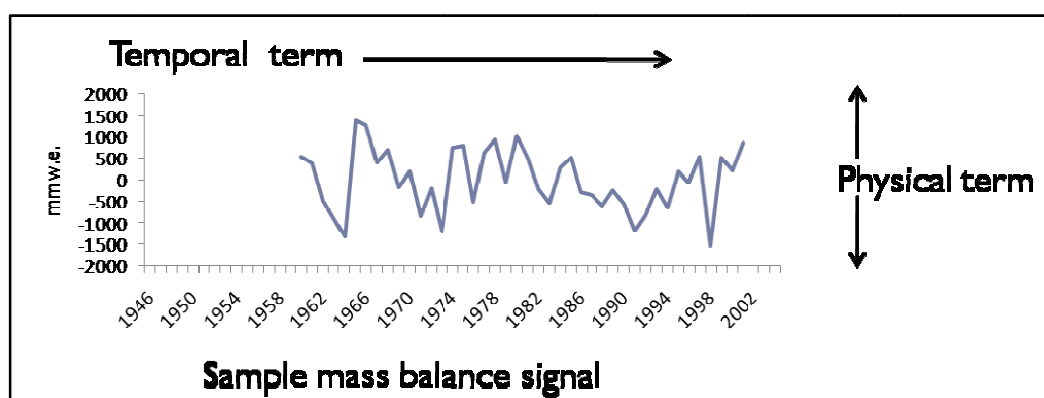


Figure 1. Sample mass balance signal indicating the temporal and physical terms

### 2.3 Regional Representation and the Temporal Component

The first objective is to define a regional temporal signal that can be linked to climatic variations at a given location. This time dependent component can also be reasonably replaced with another series from a nearby glacier within 500km (Letreguilly and Reynaud, 1989; 1990) or 200-300km (Ohmura, 2006). These authors used the linear model of Lliboutry (1974) to identify regionally similar temporal variations in glacier mass balance. Ohmura (2006) found global fluctuations were well correlated at century-long time scales, but also found regionally similar temporal variations were

found on much shorter time scales, such as decades. These results coincide well with the pioneering work of Letreguilly and Reynaud (1989; 1990). Figure 1. Haeberli (1998) indicated that a simulation of regional climate, both past and potential future, can be identified through statistical analysis of glacier datasets. More importantly a simulation of regional glacier behavior can be identified through statistical analysis of regional climate.

## **2.4 Continentality and the Glacier Specific Component**

Variations in the mass balance signal that are more specific to an individual glacier are manifest in the mass balance standard deviation and found to be dependent upon distance to a humidity source (Braithwaite and Zhang, 1999; Letreguilly and Reynaud 1989; 1990). The second objective is to extract this information based on glacier location. This glacier dependent component tends to be less well defined due to the large number of variables that influence specific glacier setting. A detailed, process level understanding of these variables is required to fully describe glaciers at the individual level. However most of the variability within this component is found to be dependent on glacier continentality (Braithwaite and Zhang, 1999; de Woud and Hock, 2005; Letreguilly and Reynaud, 1989; 1990; Meier, 1984). Maritime glaciers tend to have relatively large standard deviations and continental glaciers having relatively small standard deviations.

Early attempts to quantify the contribution of small glaciers to sea level rise led to the recognition of these characteristic differences in glaciers as a function of continentality. Meier (1984) identified a balance amplitude term, defined as the

difference in winter and summer balance where  $\alpha = (b_w - b_s)/2$ , and found balance amplitude to be dependent on glacier continentality. A similar term, defined using the absolute value of winter and summer balance where  $\alpha = [(|bw| - |bs|)]/2$  was used to describe the mass turnover of glaciers (Dyurgerov and Meier, 2000) which was confirmed by Ohmura (2006) and also related to continentality. More importantly Braithwaite and Zhang (1999) used a degree-day approach to identify a relationship between continentality and a tuned model for mass balance sensitivity to a standard  $1^\circ$  C change in temperature. In doing so they identified the relationship between glacier sensitivity and balance amplitude indicating balance sensitivity is also a function of glacier continentality.

These previous studies describe characteristics of well-studied glaciers with direct observations, especially in the case of balance sensitivity. To define the glacier specific traits of unmeasured glaciers, a term defining the degree of glacier continentality based on glacier location will be required. This term must remain as glacier specific as possible and will not be considered regionally cohesive like the temporal term identified by objective one. Ultimately the physical term will provide the basis for constraining the range of possible variation about the regionally generalized temporal component of the mass balance signal for unmeasured glaciers.



## CHAPTER 3 - METHODS

### 3.1 Data and Study Area

Recently a number of authors have compiled and inventoried scientific datasets of glacier observations (e.g. Cogley and Adams, 1998; Dyurgerov and Meier, 2002; 2005). This investigation used the compilation of Dyurgerov and Meier (2005) for glacier point locations and net mass balance time series. The Dyurgerov and Meier (2005) compilation, hereafter referred to as DM05, was ideally suited because glacier records listed are only direct observations and not records created by meteorological monitoring. This does not suggest that meteorological modeled datasets are inaccurate or less useful, however the objective was to group glaciers based on climatic data and cannot be accurately tested without the use of direct observations, independent of meteorological reconstructions.

The DM05 dataset comprises 294 records of glacier net balance, which is all of the available records of direct observations at the time of publication. Glacier specific parameters reported in DM05dataset are: Glacier Name, Country, Geographic area, Latitude, Longitude, Elevation (Maximum, Median and Minimum), Length, Area and Aspect. This dataset was compiled from records of a number of different researchers; as such some glacier records are missing some of these parameters. Large ice sheets of Greenland and Antarctica were omitted in this compilation as are outlet glaciers at the periphery of these large ice sheets. A number of glaciers in the dataset are located in the Southern Hemisphere or located south of the extent of the analysis and were

subsequently omitted. Remaining are 185 glacier records with suitable data for this analysis.

A gridded climate reanalysis was used to identify the appropriate climatologic patterns. The European Center for Medium Range Weather Forecasting (ECMWF) ERA-40 product was selected (Simmons and Gibson, 2000; Uppala et al., 2005). This is a gridded data product that is available as daily or monthly values with a spatial resolution of  $2.5^\circ$  in both latitude and longitude. For each grid cell, monthly mean data were obtained from September, 1957 to August, 2002. The ERA-40 product is a second-generation reanalysis product that was designed to account for many of the difficulties, such as temperature and precipitation biases (Bromwich and Wang, 2005) in the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Bromwich and Fogt, 2004; Gibson et al., 1997). ERA-40 has also been found to be better representative of in-situ collected data at high latitudes than the previous generation ERA-15 reanalysis (Bromwich and Fogt, 2004; Bromwich and Wang, 2005). Reanalysis data are designed as a compilation of data for a number of climatic variables where trends and evolution in data reporting systems have been accounted for and consistently assimilated.

Surface temperature fields were utilized for the creation of glaciated regions as outlined by objective one. Surface temperature is indicative of the net radiation including sensible and latent heat fluxes, which collectively comprise the largest component of the surface energy balance for glaciers (e.g. Hock, 2005). Surface temperature and combined convective and stratiform precipitation fields were utilized

to identify the degree of continentality as outlined by objective two. The ratio of warm season to cool season temperature can be used to determine continentality in terms of a distance to a humidity source (Oerlemans and Fortuin, 1992; Naito et al., 2001; de Woul and Hock, 2005; Oerlemans et al., 2005). The precipitation field is utilized as an additional parameter because the quantity of precipitation has been found to have significant influence on the specific relationships identifiable by continentality (Fujita, 2008; Ohmura, 2006). Data was acquired for the entirety of the Northern Hemisphere North of 47.5 degrees North latitude. Data acquisition was limited to the Northern latitudes to reduced the dimensionality of the data while initially testing this approach and at the same time utilizing the mass balance data from many of the most well studied Arctic and Sub-Arctic glacier systems.

### **3.2 Data Analysis Methods:**

Representation of glacier mass balance as outlined in the objectives was approached using two methods. Each method used the ERA-40 reanalysis data to enhance the irregular representations of the in-situ network of glacier observations. First, spatial correlations were derived using monthly mean temperature over the 45 year ERA-40 period of record. The correlation approach is described in further detail in section 3.4. The second method involved derivation of a scale of continentality using a combination of temperature and precipitation variance for each ERA-40 grid cell. This scale was termed the Normalized Difference Climate Index for Glaciers termed (NDCI). Enhancing the definition of continentality by normalizing with precipitation

variability creates a more physically correct representation of glacier climate. The NDCI is further described in section 3.5.

### **3.3 Data Preparation**

ERA-40 datasets were obtained using Unidata's NetCDF data structure. The spatial domain for the climate data comprised 144 longitudinal and 18 latitudinal grid cells, to cover the entire Northern Hemisphere north of 47.5°N. The temporal domain of the ERA-40 data consisted of 540 monthly values for each parameter covering a period from August 1957 to September 2002 (Simmons and Gibson, 2000; Uppala et al., 2005). Basic processing, analysis and manipulation of the datasets were performed using IDL. Dataset preparation included first totaling convective and stratiform precipitation parameters to achieve a total precipitation data set. Convective precipitation occurs at smaller scales as the result of localized lifting of air masses, stratiform precipitation occurs over larger scales as a result of frontal activity. The temporal dimension and serial correlation of the temperature dataset was reduced by calculating annual warm-season mean temperatures. Warm-season (JJA and AMJJAS) and cool-season (DJF, ONDJFM) averages and annual averages were created. Results were output to GEOTIF structured files and spatial analysis was performed with standard geographic information science GIS software, Arcmap.

The DM05 glacier parameters dataset was digitized by transforming the glacier location coordinates to decimal degrees and creating a point class shapefile to analyze the geographic distribution of glacier parameters using the GIS. The DM05 dataset was then trimmed to include only glaciers lying north of 47.5° North Latitude and

mass balance time-series longer than 12 years. The resulting dataset is comprised of data records for 80 small glaciers and ice caps in the Northern Hemisphere. These 80 glaciers were the ones defined as representative for this study. Each glacier point location was then mapped to the 2.5° by 2.5° grid from the ERA-40 datasets. When the appropriate grid cell was defined for each 80 glaciers a total of 30 unique grid cells were identified as containing at least one representative glacier.

### **3.4 Climate Correlation Regions.**

The extent of the spatial area over which a glacier was considered representative was determined by the calculation of the Pearson correlation coefficient between the evolution of mean annual temperature from 1958 to 2002 for a grid cell containing the representative glacier and every other grid cell in the spatial domain of the ERA-40 dataset. Each of the 30 grid cells containing a representative glacier was tested for correlation with every other grid cell in the spatial domain. The result is a correlation surface with a correlation coefficient indicating the degree to which each cell is correlated with the representative cell. A unique correlation surface was created for each of the 30 representative cells.

Determination of distinct regions of correlation was complicated by the high degree of spatial autocorrelation, a type 1 error (Fortin and Payette, 2002; Legendre and Legendre, 1998) found within the temperature dataset. To appropriately consider the statistical correlation a type of significance test needed to be employed. Standard methods of significance testing, with  $n-2$  degrees of freedom, identified significant correlation for nearly every cell within the spatial domain for any of the 30

representative cells. Ultimately a significance test was applied to identify those cells in each correlation surface that do not show correlation that is greater than a random series of annual temperatures. The correlation coefficient was retained at every location where correlation with the series of annual temperatures at the representative location passed this significance test.

This style of significance test, used to control for random correlation, was important in this instance because the input temperature field exhibits strong autocorrelation in the spatial domain. The output correlation surface for each of the representative cells should not indicate correlation where the level of correlation is not stronger than correlation with a series of annual temperature that has been randomly ordered. To account for the problem of spatial autocorrelation a Monte Carlo method involving random reordering of each of the 30 representative series was employed.

For the 30 correlation surfaces created from the 30 representative glaciers, a Pearson correlation coefficient was calculated 1000 times. At the location of every grid cell in the spatial domain this coefficient was calculated to define the degree of correlation with the representative series of annual temperature that had been randomly reordered. Ultimately each of the correlation surfaces had 1000 correlation coefficients that were ranked from low to high at every grid cell location. Again, at each grid cell, the coefficient filling the 990<sup>th</sup> rank was extracted and used to define the critical value to test for randomness at the 0.99 level.

The critical values for each grid cell location were used to create a critical correlation surface. This critical surface was used as a test for the original correlation value.

Where the correlation coefficient from the original surface was greater than the critical value, that original coefficient was retained. Where the original correlation value did not exceed the critical value, it was masked and considered not significantly correlated.

The Monte Carlo simulation employed at the 99% level was useful for constraining the spatial extents of the individual regions to only statistically significant areas. This accounts for correlation that occurs as the result of random chance in a dataset that exhibits inherent spatial autocorrelation. Serial autocorrelation in the temporal domain was another statistical concern when evaluating correlation using the temporal evolution of the dataset. To reduce the effects of serial correlation five different methods of seasonal averaging; JJA, DJF, AMJJAS, ONDJFM, and annual were employed. Only the warm season temperatures averaged for JJA were retained for the final analysis for two reasons. First, the geographic distribution of regions was not drastically altered by the other treatments. Second, and more importantly, the general literature suggests that the use of JJA temperature is the most physically correct approach for region creation from temperature data. Warm season temperature has been found to explain the majority of the variance in glacier mass balance (Fujita, 2008; Greene, 2005; Greene et al., 1999; Greene, Paterson, 1994).

Ultimately, a single surface depicting each of the significant correlation regions was created. Because of the relative geographic proximity of many of the representative

glaciers, a number of the significant correlation regions had overlapping extents. At locations where the significantly correlated regions from more than one of the 30 representative glaciers overlapped, the magnitude of the correlation was considered. The overlapping cell was awarded to the region containing the representative glacier that it was mostly strongly correlated with. In a few instances the regions from distinct representative glaciers were nearly identical; an alternate, simplified, correlation surface was then created by dissolving these mostly similar regions into single regions. This is similar to what is done in a Bayesian Maximum Likelihood classification in which grid cells are sorted based on their probability of membership within a class (Jensen, 2005).

### **3.5 The Normalized Difference Climate Index**

An index of glacier continentality termed the NDCI was developed by extracting a signal of seasonal temperature amplitude and precipitation variability from the ERA-40 datasets then combining the two. The NDCI derived from a temperature amplitude based index of continentality (de Woud and Hock, 2005), referred to here as the temperature index (TI). This TI a ratio of maximum to minimum temperature for a given grid cell over the dataset period of record, to determine the degree to which that cell was continental (removed from a temperature moderating source of humidity). The TI was enhanced by the addition of a term to account for precipitation variability, termed the humidity Index (HI). The HI was used to represent the precipitation variation at a given grid cell with respect to the running mean precipitation over the dataset period of record at each grid cell. The TI and HI are combined using a



normalized difference approach that results in a value describing climate regime for each grid cell ranging from -1 to 1. The value returned is indicative of the degree to which a location is “continental” based temperature stability and the relative quantity of precipitation. On this scale -1 represents wet-coastal, 0 represents wet-continental/dry-coastal and 1 represents dry-continental.

To achieve this regular scale the TI and HI needed to be treated in a very specific manner and each index needed to have range of low to high values that was rescaled to range between 0 and 100. The TI was created and then rescaled such that the low to high output values ranged between 0 and 100 (Equation 1). The calculation results in a value describing the ratio of warm to cool season temperatures. This ratio will be greatest over large land masses. Conversely, maritime and coastal areas have a smaller range of maximum to minimum temperatures due to the temperature-moderating effects of large bodies of water. Therefore those grid cells nearest to a temperature-moderating source of humidity have the smallest TI values, and those grid cells furthest from moderation will have the highest ration of warm to cool season temperatures and have the largest TI values

$$\left( \left( \frac{\alpha_{ij}}{\beta_{ij}} \right) \left( \frac{1}{a_{max} - \beta_{min}} \right) - \left( \beta_{min} \left( \frac{1}{a_{max} - \beta_{min}} \right) \right) \right) \text{ eq. 1}$$

Where  $\alpha$  is the average of all temperatures greater than the mean at cell  $i,j$  and  $\beta$  is the average of all temperatures less than the mean at cell  $i,j$ .

The effects of extreme warm or cold temperatures were eliminated by using the average of all temperatures above and below the mean temperature for the respective maximum and minimum temperatures at each grid cell location. This eliminated the need to identify warm and cold season averages from arbitrarily defined warm seasons, which can be quite variable across large spatial extents. Doing so also reduced the effects of outliers resulting from anomalously warm or cold months that may have occurred at some point over the 45 year record.

Precipitation data were treated similarly to create the HI. However, an amplitude style ratio was not used. Such a ratio of maximum to minimum precipitation would identify variability within the precipitation dataset; similar to the approach used for the temperature dataset. Instead the relative magnitude of precipitation for each cell was calculated by dividing the mean precipitation at each grid cell by the mean precipitation for all grid cells. Again, the results were rescaled such that the values range between 0 and 100 (Equation 2).

$$\left( \left( \frac{\bar{\rho}_{ij}}{\bar{\rho}_{ij}} \right) \left( \frac{1}{\bar{\rho}_{max} - \bar{\rho}_{min}} \right) - \left( \bar{\rho}_{min} \left( \frac{1}{\bar{\rho}_{max} - \bar{\rho}_{min}} \right) \right) \right) \text{ eq. 2}$$

Where  $\bar{\rho}_{ij}$  is the mean precipitation value at cell  $i,j$  and  $\bar{\rho}$  is the mean precipitation value for all locations. This calculation used all precipitation values regardless of season. HI values that are relatively high represent areas with more precipitation.

The two indices were combined using a normalized difference index approach (Equation 3). This approach is commonly used in remote sensing to account for

variability in surfaces that reflect strongly in one band but have an opposite response in another. This is why the TI and HI were designed to range from 0-100 and also why areas of expected low precipitation have a high value in temperature index, but a low value in the humidity index. The index is normalized in this manner to return a value that ranges from -1 to +1 and describes the degree of continentality based on temperature and precipitation variability for a given grid cell.

The benefit of a normalized value is that the sign of the output provides a clear indication of which input parameter is dominant. The temperature index parameter is dominant for all positive returns; the humidity parameter dominates all negative returns. NDCI returns closer to zero indicate smaller input parameter ratios, and values with a magnitude closer to 1 indicate larger input ratios, a situation where the input parameter, temperature or humidity, shows strong dominance.

$$NDCIG = \left( \frac{TI-HI}{TI+HI} \right) eq. 3$$

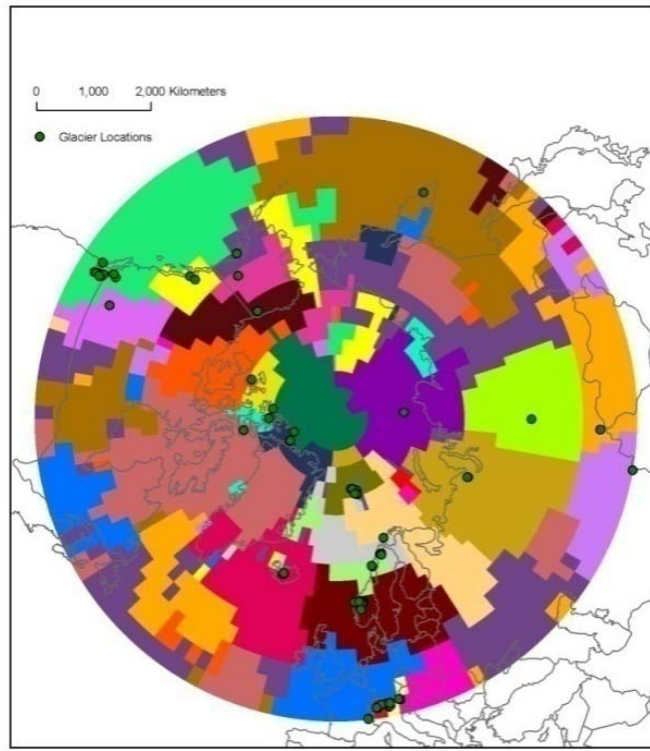
Where TI equals the temperature index and HI is the Humidity index from Equations 1 and 2. Equation 3 returns a value that is positive for glaciers with a TI value greater than the HI value. This positive value approaches +1 for glaciers with a TI value much greater than the HI value, continental and dry. A negative value will be returned for glaciers with a TI value less than the HI value. This negative value approaches -1 for glaciers with a TI value much less than the HI value, coastal and wet. Glaciers with a TI value are only slightly greater than the HI or vice versa may be positive or negative, respectively, and close to zero, indicating varying degrees of marginally wet

and marginally continental. Ultimately all glaciers can be placed along this coastal-wet to continental-dry continuum.

## CHAPTER 4 - RESULTS

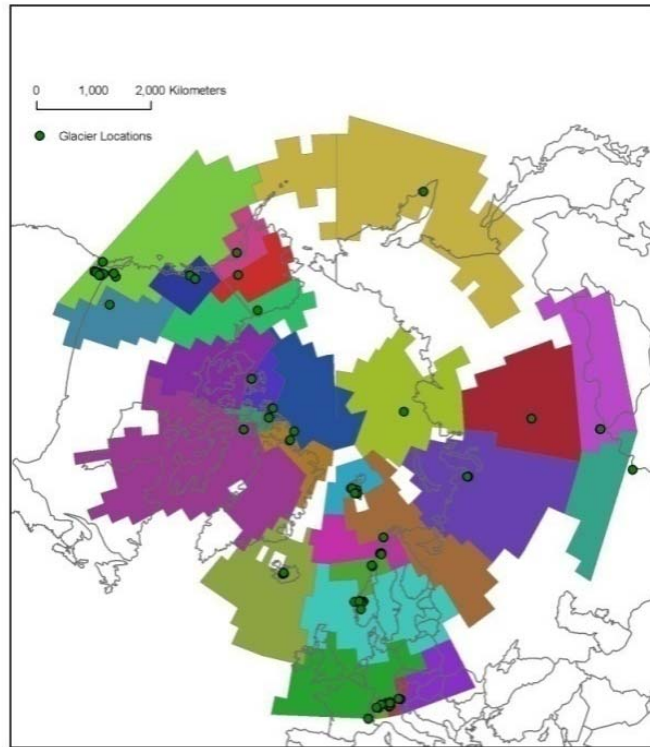
### 4.1 Point Correlations

Point correlation analysis described in Section 3.3 and performed on 30 different representative grid cells resulting in 30 individual correlation surfaces. Figure 2 identifies the extent of all significant correlation regions. Figure 2 is the result of combining all 30 of the correlation surfaces to a single surface to identify which representative grid cell the other grid cells were most strongly correlated with. This process results in a grouping of cells with similar temporal patterns. These groupings are the regions that have a temporal evolution of summer temperature from 1957 to 2002 most similar to the temporal evolution of one of the representative cells. The result is 36 distinct regions. This is six more regions than representative cells, because some of the regions show a temporal evolution of summer temperature that is correlated more strongly with a non-adjacent grouping of cells, or region. These regions do not presently contain any representative glaciers and might be thought of as “orphans”.



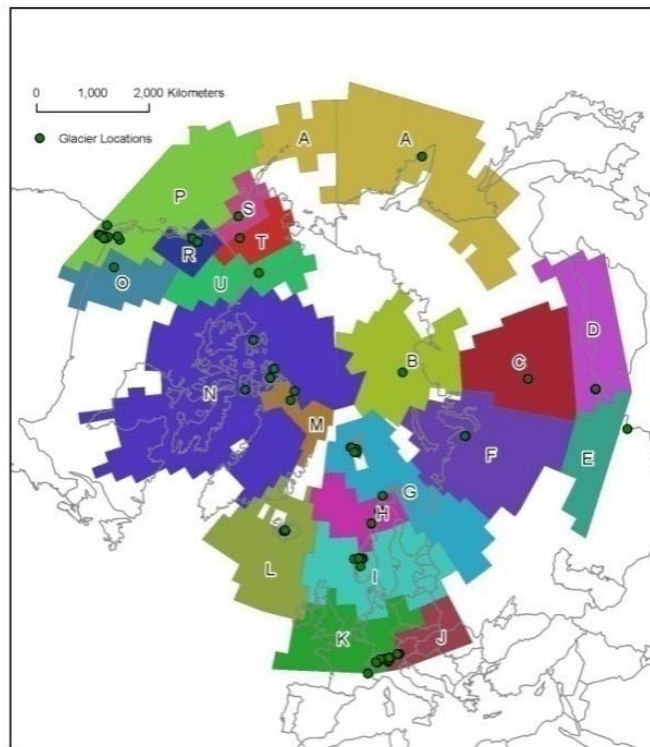
**Figure 2. Correlation analysis results of 30 representative glaciers returns 36 distinct regions.**

Correlation regions consisting of groupings of adjacent cells are depicted by Figure 3. Each of the 30 representative glaciers is identified along with the adjacent cells that have a temporal evolution of summer temperature most strongly correlated with that representative cell. There are 30 distinct regions of the most strongly correlated cells.



**Figure 3. Correlation regions (30) that contain at least one representative glacier.**

A number of these regions have similar spatial patterns of correlation. This is the case among some cells in the Alps, the Scandinavian Peninsula and the Canadian Arctic archipelago. Those regions that show similar spatial patterns of correlation were further simplified by manual aggregation.



**Figure 4. Correlation regions identified as unique (21) and labeled according to Table 2.**

Through this process the total number of distinct regions drops from 30 (one region for each representative cell) to 21 (one region for each distinct spatial pattern of correlation) as shown in Figure 4. The distinct regions identified in Figure 4 are alphabetically labeled and the corresponding region descriptions are found in Table 2.



**Table 2. Unique point correlation regions identified in Figure 3**

<b>Region</b>	<b>Area Description</b>
<b>A</b>	Kamchatka Peninsula
<b>B</b>	Severnaya Zemlya, extending 1000 km in every direction
<b>C</b>	Central Russia, shared North Border with B
<b>D</b>	Altai, in South Central Russia, including Mongolia shares N border with C
<b>E</b>	Kazakhstan, South Western Russia, shares W border with D, extends to Caspian
<b>F</b>	Polar Ural Mountains, North Russia including Novaya Zemlya, bounded by B,C,D,E,G and H
<b>G</b>	Svalbard, bounded by F and H
<b>H</b>	North Coast of Norway, Finnmark, Kebnekaise and Svartisen, bounded by G and I
<b>I</b>	Southern Norway, Jostedal, Alftobreen and Jotunheimen South of H
<b>J</b>	Eastern Alps, Austria and Far East Switzerland toward cont. Europe
<b>K</b>	Western Swiss and French Alps, shares East border with J
<b>L</b>	Iceland and East Coast of Greenland
<b>M</b>	Canadian Arctic, Ellesmere Island including N and NW Greenland
<b>N</b>	Canadian Arctic, Axel Heiberg, Baffin, Devon, Melville Islands, shares border with M, T
<b>O</b>	Northern Rocky Mountains, bounded by P, R, U
<b>P</b>	North Cascade Mountains and Western British Columbia, bounded by O and Q
<b>Q</b>	Olympic Mountains, bounded by P and R
<b>R</b>	SE Alaska, Juneau Ice Field, bounded by O,P,R,S,T,U
<b>S</b>	S Coastal Alaska, Aleutian Range, Kenai, Chugach and St. Elias Ranges, Bounded by R,T
<b>T</b>	Central and Continental Alaska, bounded by S,U
<b>U</b>	Northern Alaska, Brooks Range, bounded by T,N

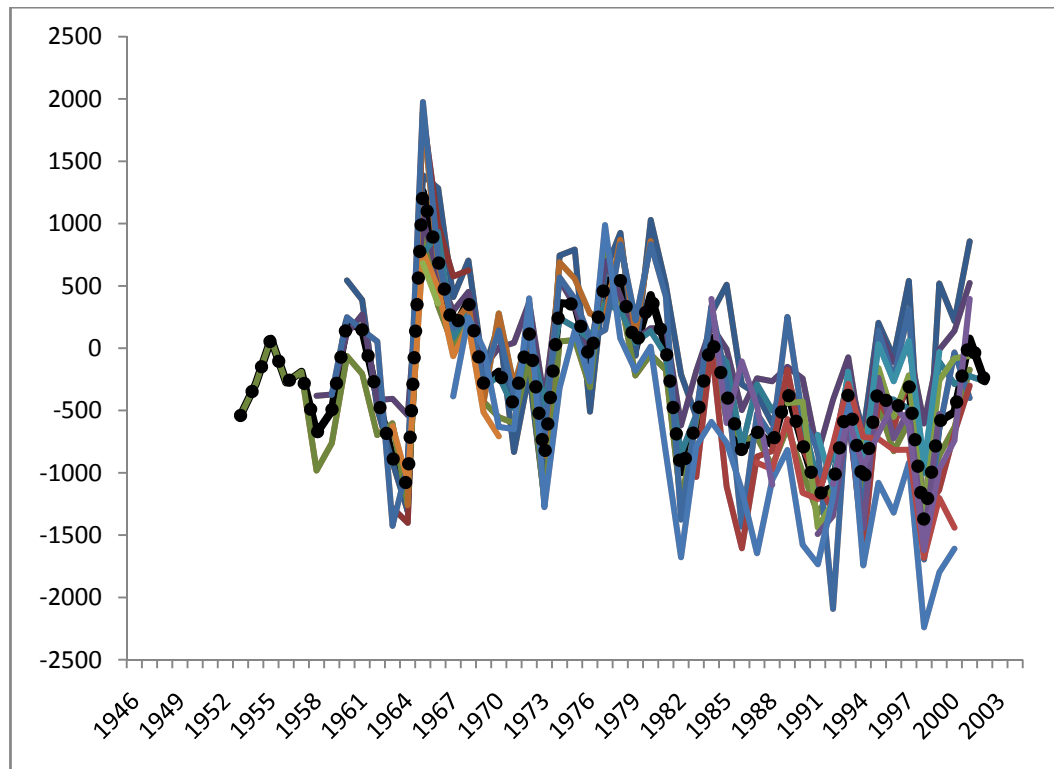
The main glacier systems of continental Europe are examined in more detail. In the case of the Alps and the Scandinavian Peninsula, original correlation analysis (Figure 3) indicates multiple distinct regions. Thorough analysis of spatial correlation patterns for these regions identified four distinct centers of correlation. These regions identified as the East and West Alps and North and South Scandinavia can be seen in Figure 4 and Table 2. Each of these regions was explored individually to determine the extent to which the evolution of the mass balance time series within each region was correlated. Whether or not that mass balance series correlation within each region

is stronger than correlation when the regional boundaries are extended to include its mountain system neighbor was examined as well. These results are summarized in Table 3.

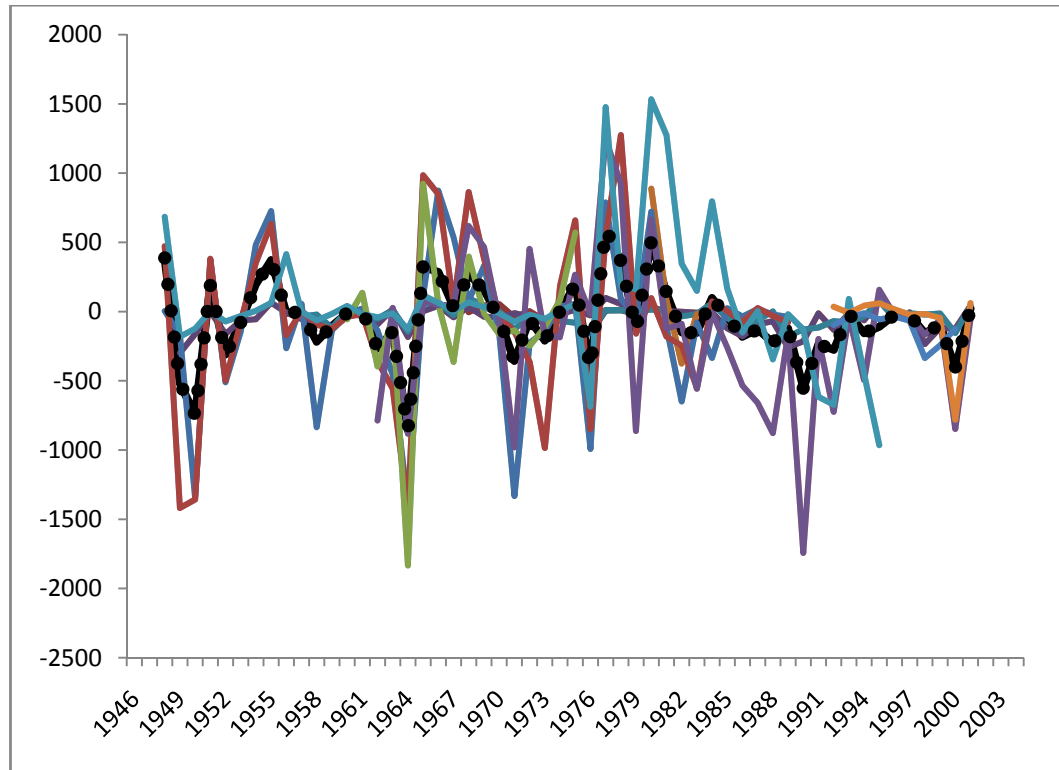
**Table 3. inter and intra-region correlation analysis for the East and West Alps, Regions J and K, and North and South Scandinavia, Regions H and I**

<b>Region</b>	<b>J</b>	<b>K</b>	<b>H</b>	<b>I</b>
<b>Geographic Area</b>	E. Alps	W. Alps	N. Scan	S. Scan
<b>Count</b>	16	16	21	25
<b>Mean correlation between in-region glaciers and:</b>				
<b>In-region glaciers</b>	0.73	0.53	0.70	0.67
<b>Representative series for the region</b>	0.89	0.72	0.89	0.85
<b>Representative series for the adjacent region</b>	0.64	0.55	0.68	0.56
<b>Representative series for the mountain system</b>	0.87	0.63	0.79	0.83
<b>Representative series for all 185 glaciers</b>	0.60	0.40	0.36	0.28

Analysis of the temporal evolution of temperature patterns within the Alps suggests two distinct patterns, regions J and K. The evolution of the mass balance series within each region is indicated by Figure 5 and Figure 6. Each region has a distinct representative time series, as indicated by the mean or regionally representative series, depicted by the black dashed line. For regions J and K, inter and intra-region correlation values are strong. Mean correlation among all glaciers in region J is 0.73 and mean correlation among all glaciers in region K is 0.53. Mean correlation among all glaciers in the Alps as a single unit is 0.52.



**Figure 5.** East Alps, Region J, Y-axis is net mass balance in  $\text{mmw.e. yr}^{-1}$ .

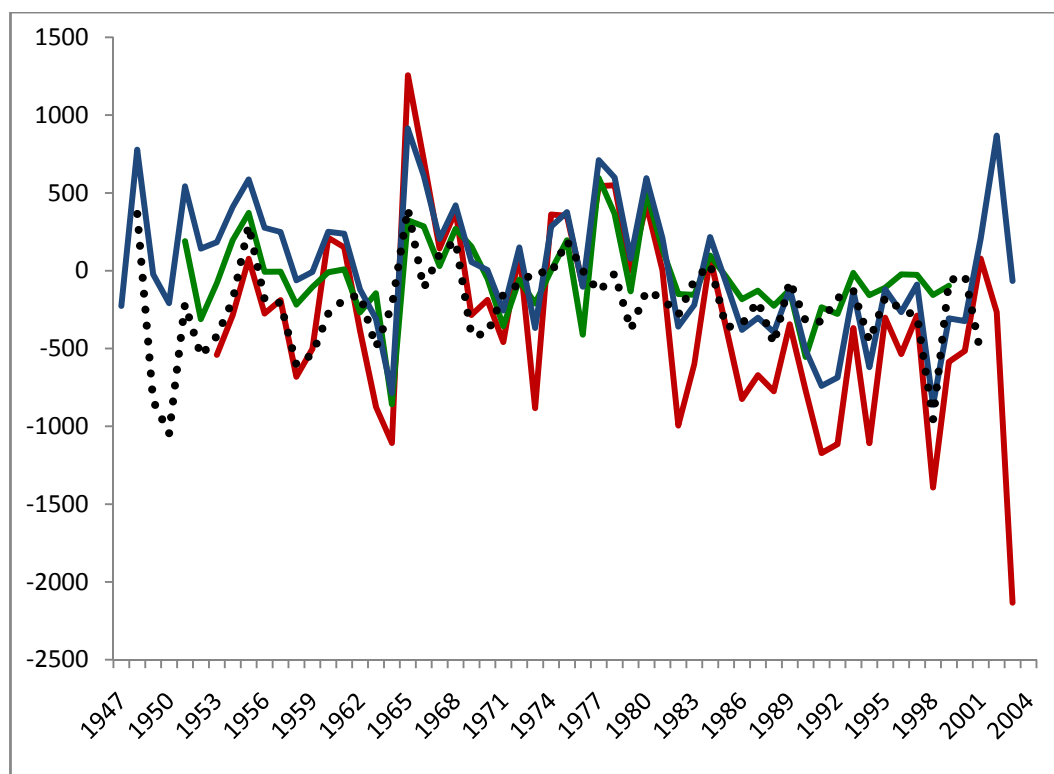


**Figure 6. West Alps, Region K, Y-axis is net mass balance in mmw.e. yr<sup>-1</sup>.**

The mean net balance time series calculated for each region is considered the “representative” series. In other words, this series is representative of the mean temporal variation within the region. The correlation coefficients among each glacier in the region and the regional representative time series were determined. For region J the average correlation for all glaciers within the region with the representative time series is 0.89. Correlation between region J glaciers and the region K representative series is 0.64. For region K the average glacier correlation for all glaciers within the region with the representative time series is 0.72. Correlation between region K glaciers and the region J representative series is 0.55.

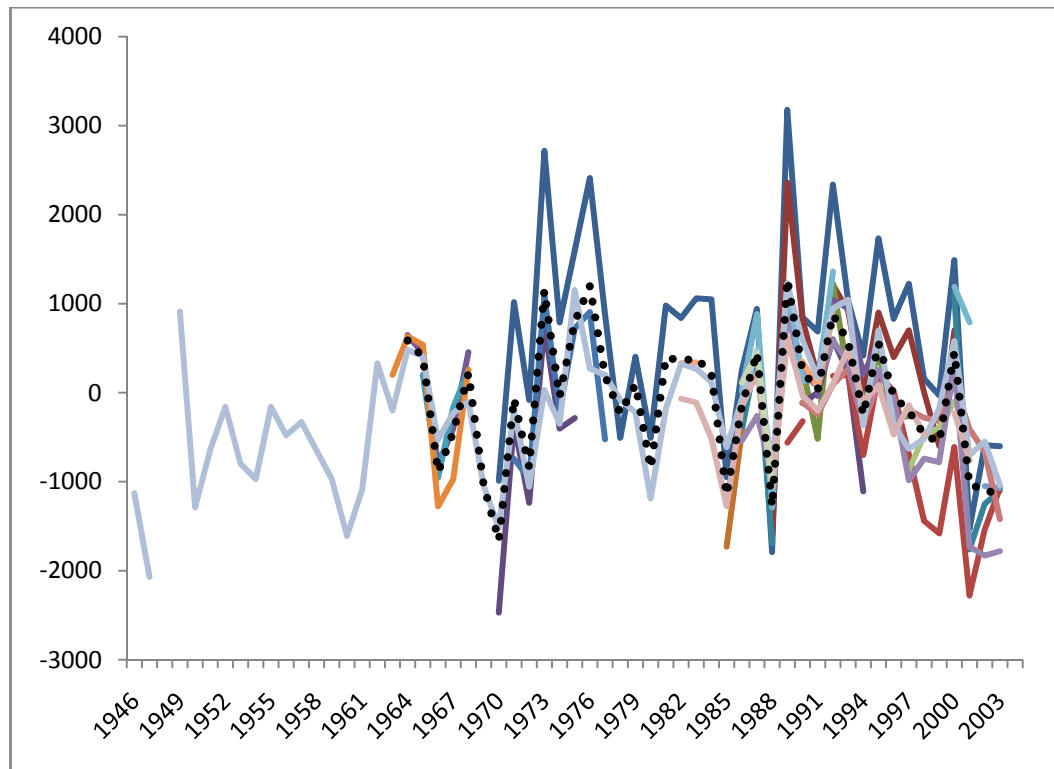
A mean balance series was also calculated for the Alps as a single region.

Correlations for glaciers within each region with the mean series for the Alps as a single system were calculated. Mean correlation among all glaciers in region J and the mean for the entire Alps system is 0.87; among all glaciers in region K and the mean for the entire Alps system is 0.63. To put the former correlations in perspective, a mean balance series for all 185 glaciers utilized in this study was calculated (Figure 7). Correlations between the mean series from each region, the Alps system and the entire system were calculated and also found in Table 3. Correlation between the entire system and region J is 0.60, region K is 0.40 and the Alps system is 0.49.

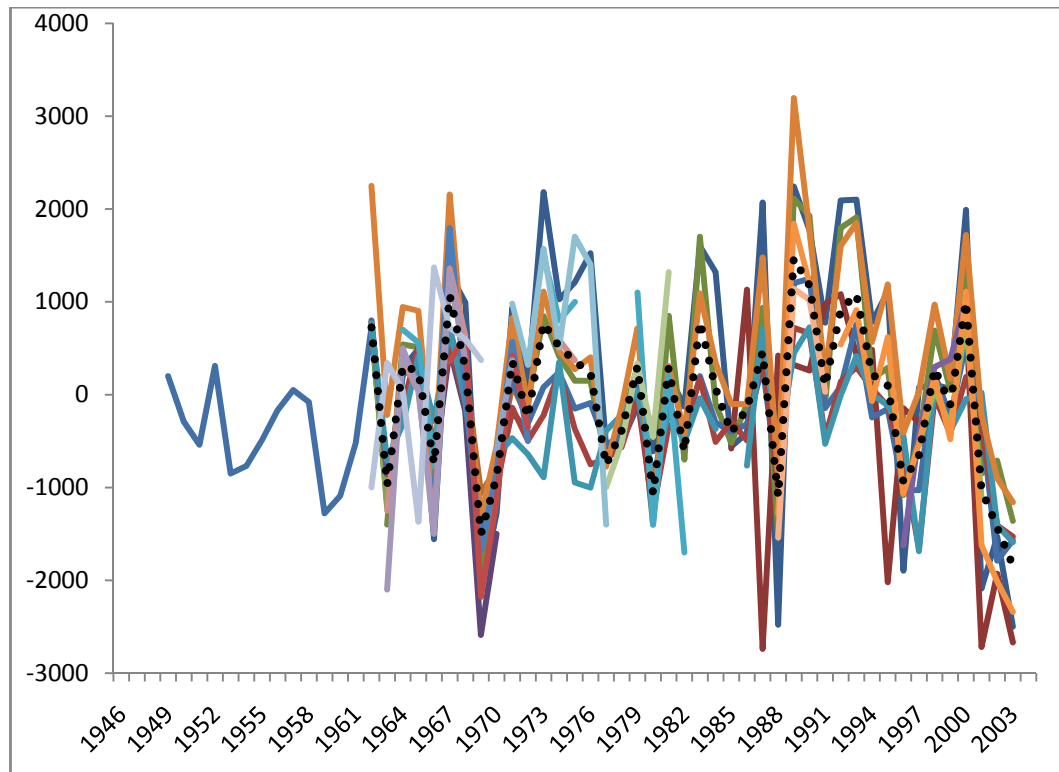


**Figure 7.** Mean net balance for region J (red), region K (green), Regions J & K combined (blue) and all 185 glaciers (black dashed), Y-axis is net mass balance in mmw.e. yr<sup>-1</sup>.

A similar analysis was performed for the two regions identified for mainland Scandinavia. Region H, North Scandinavia, and Region I, South Scandinavia, are investigated in this manner and correlations can be found in Table 3. Mean correlation for all glaciers within region H is 0.70, and is 0.67 for all glaciers in region I. The mean correlation among all glaciers inside this region when treating it as a single unit is 0.59. A mean, “representative”, time series for each region (black dashed line in Figure 8 and Figure 9) is strongly correlated with the individual glaciers within each region, 0.89 for region H and 0.85 for region I. These inter-region correlations are much better than the intra-region correlations from the adjacent region. The mean correlation value among all glaciers within region H and the representative series from the adjacent region I is 0.68. Among all glaciers within region I and the representative series of the adjacent region H is 0.56.



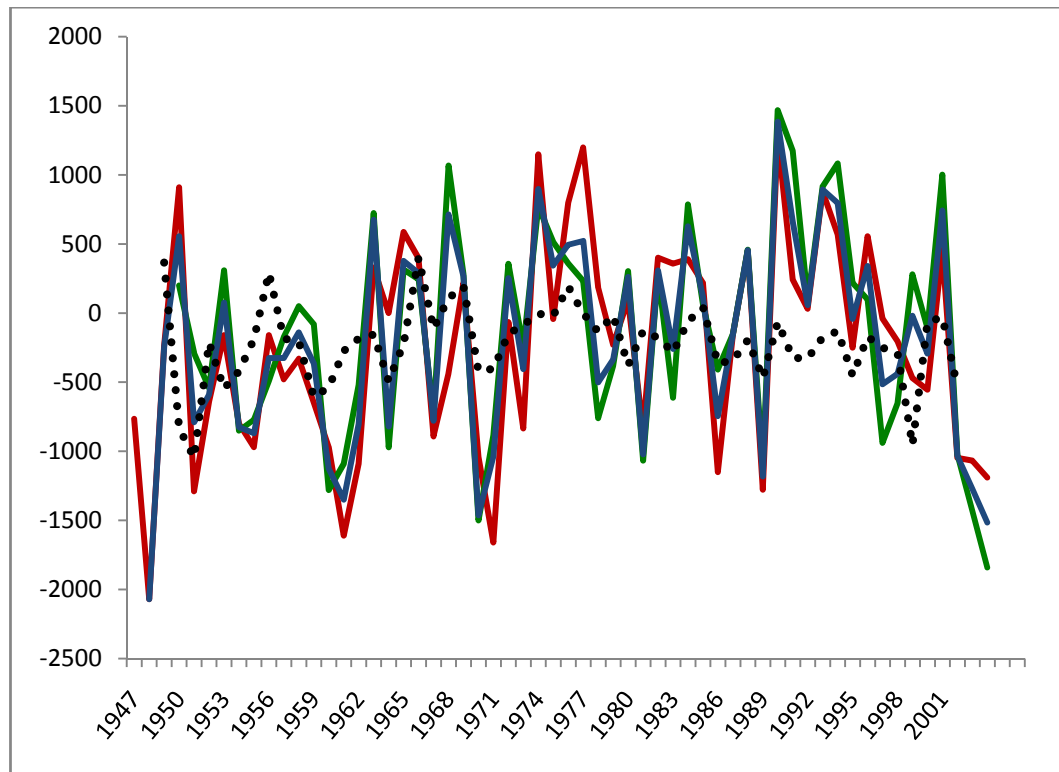
**Figure 8.** North Scandinavia, Region H, Y-axis is net mass balance in mmw.e. yr<sup>-1</sup>.



**Figure 9. South Scandinavia, Region I, Y-axis is net mass balance in mmw.e. yr<sup>-1</sup>.**

Figure 10 depicts the mean net balance for region H (red), region I (green), Regions H & I combined (blue) and all 185 glaciers (black dashed). Mean correlations for North and South Scandinavian glaciers with a representative series for the two regions combined is 0.79 for region H, and 0.83 for region I. The mean correlation value for glaciers in region H with the entire system of 185 glaciers is 0.36. Region I glacier correlation with the entire system is 0.28. The correlation of all glaciers of mainland Scandinavia with the entire system is 0.34.

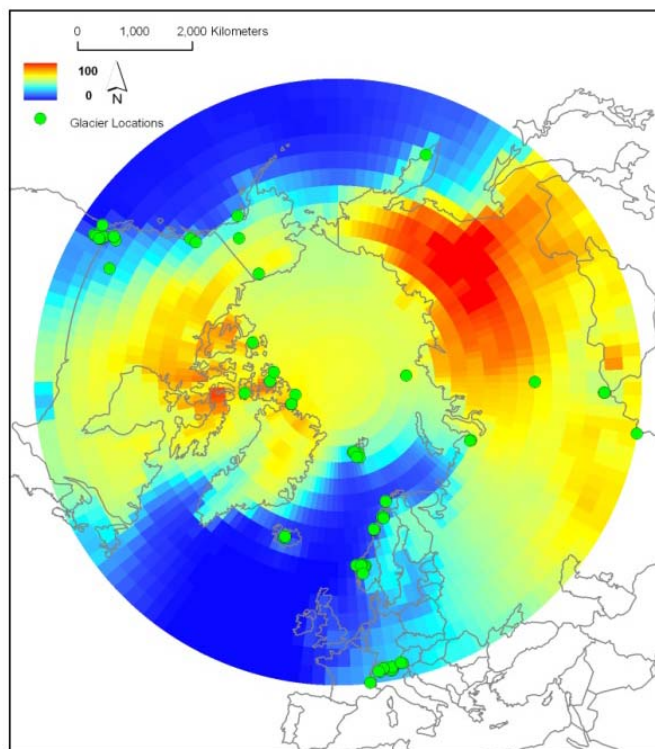




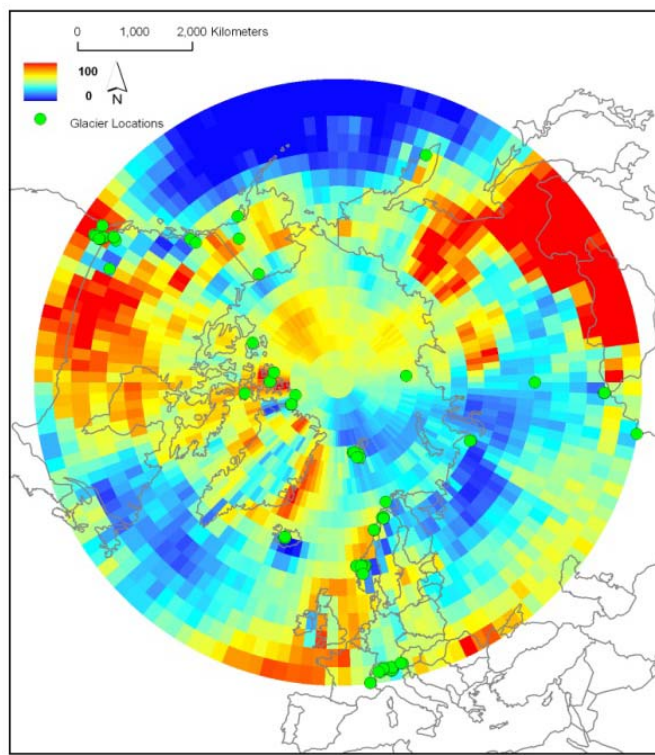
**Figure 10.** Mean net balance for region H (red), region I (green), Regions H & I combined (blue) and all 185 glaciers (black dashed), Y-axis is net mass balance in mmw.e. yr<sup>-1</sup>.

## 4.2 NDCI

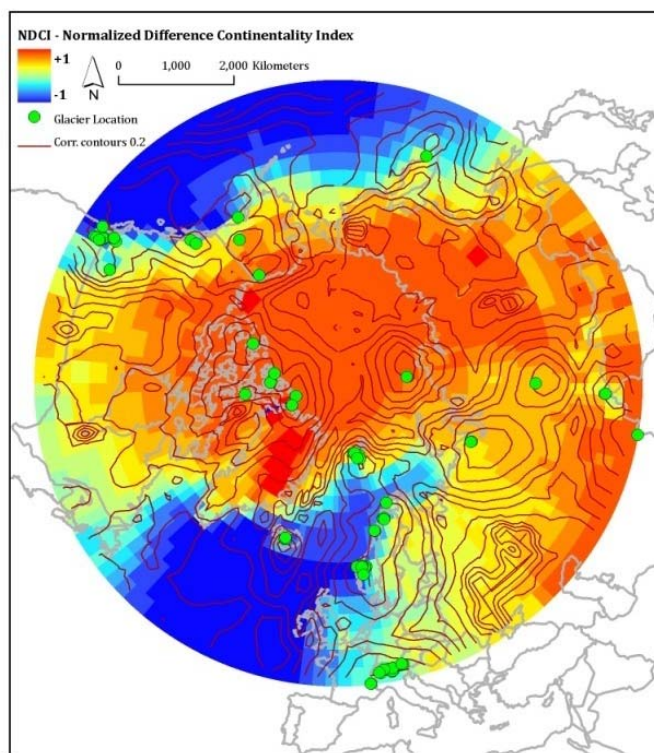
The NDCI was created from the temperature and humidity indices. The temperature index (Figure 11) ranges from 0 (blue and maritime) to 100 (red and continental). The humidity index (Figure 12) also ranges from 0-100 indicated by blue (relatively dry) and red (relatively wet). The TI and HI were combined by differencing, and the resulting NDCI (Figure 13) ranges from -1, indicated by blue (wet and maritime) and +1, indicated by red (dry and continental).



**Figure 11. Temperature Index, values range from 0-100 indicating maritime to continental (blue to red).**



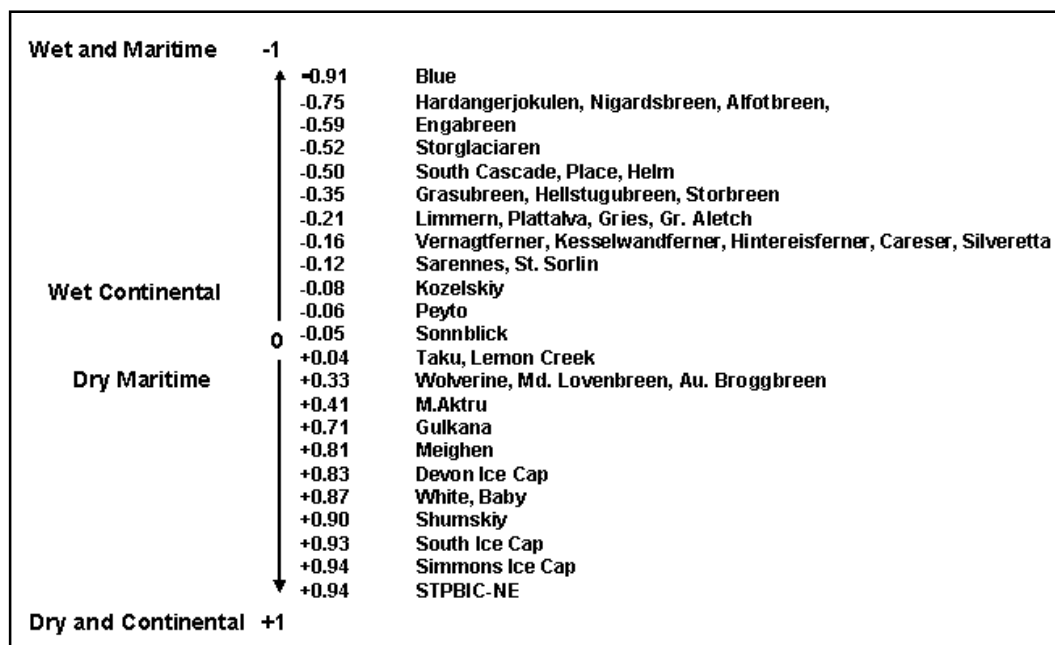
**Figure 12. Humidity Index, values range from 0-100 indicating relatively dry to relatively wet (blue to red).**



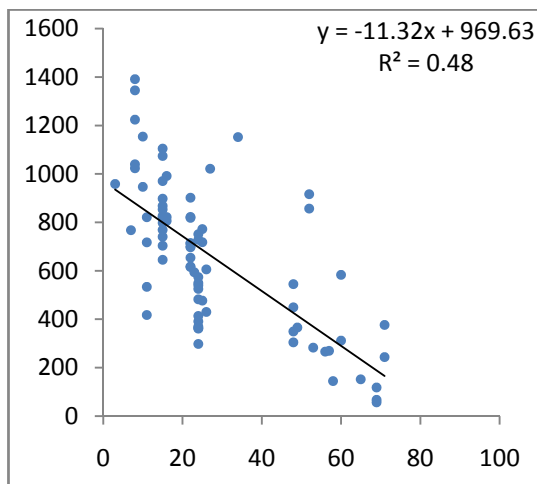
**Figure 13, NDCI ranging from -1 (blue) to +1 (red) with contours lines (red) representing contour intervals of 0.2.**

A specific NDCI value was calculated based on the reported location of all 80 glaciers considered representative for this study, glaciers with mass balance time series longer than 12 years. From this dataset of glaciers NDCI values range from -0.9 for Blue Glacier in the Olympic Range to 0.9 for White and Baby Glacier at Axel Heiberg Island, the ice caps of Ellesmere and Melville Island and Shumskiy Glacier in Kazakhstan. An abbreviated list of these glaciers is found in Figure 13, which reports the specific NDCI value for all glaciers with a mass balance series greater than 25 years in length.

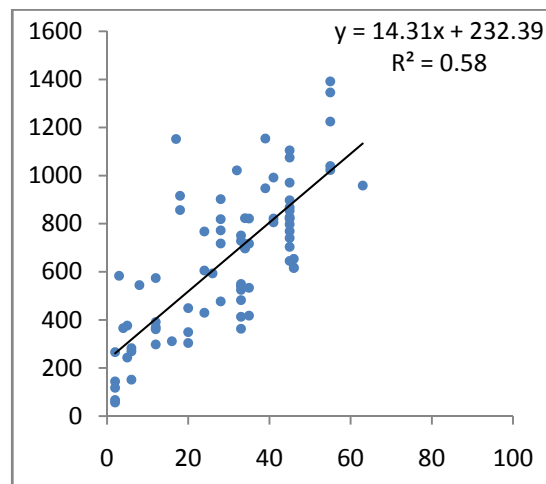
Table 4. NDCI continuum for representative glaciers with more than 25 years of mass balance data



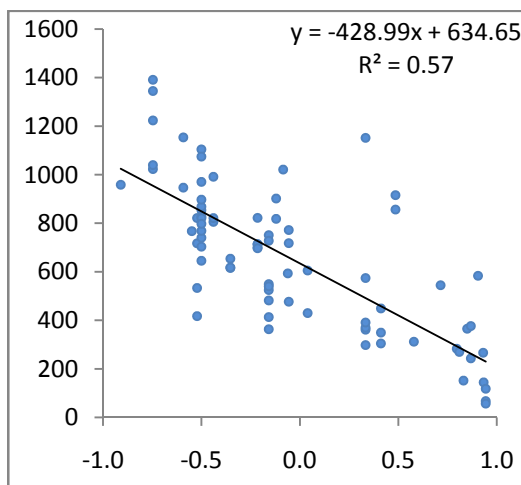
The intention of the NDCI is to represent individual glacier variability, so the TI, HI and NDCI were compared with standard deviations of net balance within the DM05 mass balance dataset. Figure 14 is a scatter plot of net mass balance standard deviations from the 80 representative glaciers (time series longer than 12 years) and TI. The  $R^2$  between these two parameters is 0.48 suggesting a fairly strong relationship between TI and net mass balance deviations. A stronger relationship was found between HI and the net mass balance deviations of representative glaciers,  $R^2$  of 0.58 (Figure 15). Normalizing the continentality index by the humidity index, the NDCI, also returns a strong linear relationship (Figure 16). The NDCI fits the net balance variance with an  $R^2$  of 0.57, slightly worse than the humidity index alone. Regressions are all significant at a  $p < 0.01$  level.



**Figure 14.** Standard deviations in mm w.e. of 80 representative glaciers regressed with TI.



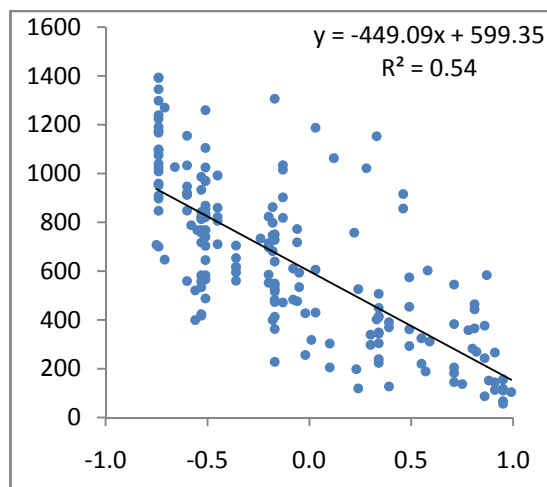
**Figure 15.** Standard deviations in mm w.e. of 80 representative glaciers regressed with HI.



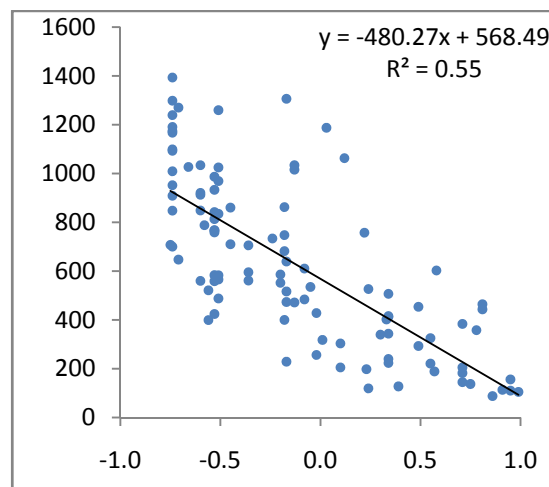
**Figure 16.** Standard deviations in mm w.e. of 80 representative glaciers regressed with NDCI.

The relationship between the NDCI and the group of 80 representative glaciers is nearly identical to the relationship between the NDCI and the full set of 185 Northern Hemisphere glaciers (Figure 17). The same can be said for the group of 105 lesser studied glaciers (Figure 18). For each of the three glacier groupings represented by

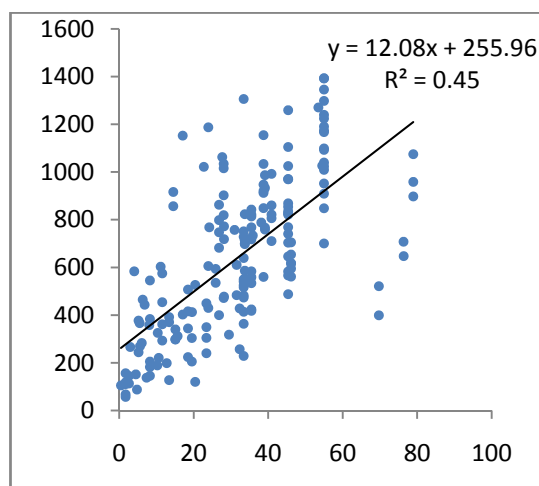
these figures, the  $R^2$ , slope, and intercept of the line remain remarkably constant. The addition of 105 lesser studied glaciers marginally increases the slope of the regression. The full set of 185 Northern Hemisphere glaciers was also compared to the individual humidity (Figure 19) and temperature (Figure 20) indices. Calculated  $R^2$  values between the full set of glaciers and HI and TI are 0.45 and 0.48 respectively.



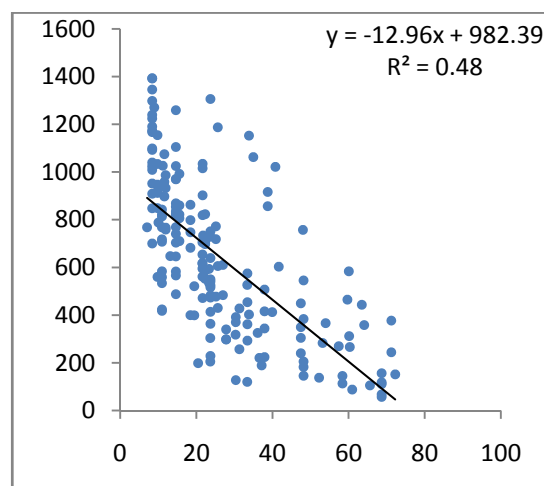
**Figure 17.** Standard deviations in mm w.e. of all 185 glaciers regressed with NDCI.



**Figure 18.** Standard deviations in mmw.e. of 105 lesser studied glaciers regressed with NDCI.



**Figure 19.** Standard deviations in mmw.e. of 185 representative glaciers regressed with HI.



**Figure 20.** Standard deviations in mmw.e. of 185 representative glaciers regressed with TI.

## **CHAPTER 5 - DISCUSSION**

One of the most interesting aspects of this approach to characterizing the glacier mass balance signal was the quality of results achieved through very simple use of two climatic parameters. The basis for this study was research published by Letreguilly and Reynaud (1989; 1990) that utilized principal components analysis to identify two principle modes of variation in a number of mass balance time series. The first component was a characteristic temporal evolution that was dependent upon glacier geographic location and is regionally cohesive. The second component was a glacier specific component, largely dependent on proximity to a moisture source. The present study defines the original component interpretations using specific climatic parameters. As more quality climate data and more direct glacier measurements become available, the relationship between glaciers and climate should become more clearly defined.

### **5.1 Correlations**

The DM05 dataset was compiled with the aim to use glacier observations to derive an estimate of sea-level change from small glaciers and ice caps that occur as a result of changes in global temperature. To derive this estimate Dyurgerov and Meier (2005), grouped measured glaciers into regions and used those measured changes within a particular region to represent the changes of unmeasured glaciers. For this purpose they geographically group glaciers into climate regions. Their geographic grouping was used as a point of comparison for the climatically derived regions of the present study.



Regions derived by point correlation analysis allow the particular extent of each region to be defined via homogeneous variation in summer temperature. Size and shape of the individual regions defined is varied. This variation in region size was largely a function of the spatial distribution of those glacier datasets deemed representative. The basic patterns of correlation depicted by Figure 4 appear to exhibit a spatial pattern dependent upon 3 main variables; 1) continentality, 2) latitude and 3) division by significant geographic barriers. Many of the individual regions identified as significant largely extend beyond the generally recognized correlation range of 500 km identified by Letreguilly and Reynaud (1990) or the 200-300km range identified by Ohmura (2006).

Areas with a high density of measured glacier datasets, such as in the Alps, result in a larger number of discrete regions. In these relatively data rich locations, multiple regions adjoin each other thus the spatial extent of the region tends to be smaller, e.g. Southeastern Alaska and Europe. The spatial extent of regions defined in areas with high density of glacier mass balance data exhibit a size of roughly 1000 km<sup>2</sup>. Because the representative glacier is usually near the region centroid, these smaller regions are arranged such that most of the ice masses within the region are actually located within a 500-km radius of a representative glacier. The extent of these regions conforms closely to the aforementioned published ranges of expected correlation. This separation of regions in data rich locations is an indication of either strong climatic variability or is a relic of the correlation method dependence on a representative grid cell. In either case this is an indication that, given sufficient

representative glacier datasets, the correlation method is sensitive to spatial and temporal variability within the temperature reanalysis dataset. To address objective one, the temporal coherence of the mass balance signal for the regions continental Europe were further investigated. Results indicate strong coherence within these regions on the scale of mountain ranges, but stronger regional coherence when the glacier groups are further divided by variability in temporal evolution of surface temperature. The following sections further discuss these results.

### ***5.1.1 The Alps***

The glacier systems of the Alps have historically been treated as one homogeneous region singularly defined by the Alps, for the one predominant mountain range feature. Identification by mountain range is fairly intuitive for identification of a region of potentially homogeneous glacier behavior. In the case of the Alps, this approach is made particularly straightforward by lack of any immediately adjacent glaciated mountain ranges, such as those found in Alaska or Mainland Scandinavia. Even the fairly detailed assessment of Dyurgerov and Meier (2005), which identified 49 primary glacier systems, identifies the Alps as single system.

Using the available representative mass balance series in the Alps, the original correlation analysis (Figure 3) actually identified four discrete regions of surface temperature variability. More detailed analysis of the spatial correlation patterns for each of these original regions led to simplification of the four regions into two distinct centers of correlation. One correlation center for glaciers in the Eastern Alps (region J) and one centered on the Western Alps (region K).

Generally speaking, glaciers of the Eastern Alps, region J, appear to have a more pronounced negative trend and greater inter-annual variability. Whereas glaciers of the Western Alps, region K, have more muted variability and are generally closer to equilibrium. Also notable was the difference in overall net balance trends between the two regions. These trends, calculated by simple averaging of the trends for each glacier, indicate an annual mass loss trend of approximately  $10 \text{ mm w.e. yr}^{-1}$  over the period of record for region J and an annual mass loss trend of roughly  $1.5 \text{ mm w.e. yr}^{-1}$  for region K.

More specifically mean correlation values for the regions within the Alps (Table 3) indicate net balance variation with time is coherent both within each individual region and among all glaciers in the Alps considered as a single region. A mean net balance series calculated for each of the regions to help to indicate the extent to which glaciers within that region might be represented by an averaged mass balance series. Comparison of this mean, representative, series with all of the glaciers within a region indicates that the representative series for region J is a better representation of those glaciers found in region J than is a representative series calculated from the glaciers of region K, 0.89 versus 0.64. Region K glaciers are correlated with the representative series for region K at 0.72, versus 0.55 with the representative series from region J indicating that the representative series for region K is a more appropriate representation of variability within that region. This would be expected considering the mean series was derived from each of the individual series of the region. This correlation derived from adjacent, but completely independent, data might be thought

of as the lower bounds for the expected temporal correlation between the representative net balance series and the actual net balance series of an unmeasured glacier that might be temporally represented using this information. In a system as well studied as the Alps it is comforting to know all glaciers within one region are, on average, correlated to the representative series from a neighboring region at a level of at least 0.55.

Considering correlations calculated for the Alps as an entire system (0.87 for region J and 0.63 for region K) and for all 185 glaciers, 0.60 (region J) and 0.40 (region K), it is evident that overall temporal variability among all glaciers within the Alps system is fairly low. However, glaciers within the system are indeed better represented when the system is treated as two distinct regions, 0.89 (region J) 0.72 (region K). This point is reinforced, as previously indicated, by the relative strength of the correlation between the glaciers and the representative time series derived from glaciers within the region compared to that derived from glaciers of the adjacent region.

The similarity of mean correlation values for region K and the Alps as a single unit indicated variability among glaciers identified in region K is roughly similar to the variability among all glaciers of the Alps. However, variability among glaciers within region J is reduced from variability over the entire Alps. Despite this fact, the East Alps, Region J, exhibits the most coherent temporal evolution. Temporal coherency among the glaciers of region K suffers notably from the net balance series of three glaciers in particular; Gries, Limm + Platt and Plattalva. These three series appear to have a temporal evolution more indicative of those glaciers found in Region J. This

may be the result of coarse spatial resolution of the reanalysis data used to define regions. The resolution of  $2.5^\circ$  by  $2.5^\circ$  cells dictates that all glaciers found within a given cell be lumped with those other glaciers within the same cell. The potential exists that some glaciers landing inside one of might be mistakenly misclassified. The error is more likely to occur at lower latitudes where the geographic distances between meridians are larger and each grid cell therefore encompasses a larger geographic area.

Misrepresentation may also be the result of an interpretation error. The three offending glaciers were all found in the same one of four original correlation units, as identified in Figure 3. These four discrete units were aggregated into two units, identified in Figure 4 and Table 2, as the East and West Alps. This aggregation was manually performed by investigation of the spatial correlation patterns for each of the original four regions. The original region containing Gries, Limm + Platt and Plattalva might have been more appropriately placed with region J as opposed to region K.

Despite the inclusion of these three potentially misclassified glaciers, the mean series (black line in Figure 5 and Figure 6) for each region still has a distinctive temporal component. This point is further evident when comparing the mean series in Figure 7. However correlations found within region K are clearly the poorest (Table 3) and are improved when the four glaciers are moved from region K to region J. These mean correlation values between all glaciers within each region corroborate the above point that some of the glaciers found in region K might have been more accurately represented by the temporal variation within region J.

### ***5.1.2 Mainland Scandinavia***

The correlation method also identifies two regions of distinct temporal evolution in temperature along the West Coast of mainland Scandinavia. The two regions identified on mainland Scandinavia have also previously been treated as a single unit (e.g. Dyurgerov and Meier, 2005), although the Scandinavian units are more likely to be treated individually than are the regions identified in the Alps, (e.g. de Woul and Hock 2005). Net balance series of the glaciers of the two Scandinavian regions are quite similar (Figure 8 and Figure 9) with minor exceptions. Region I has a greater number of glaciers demonstrating a relatively large balance spike in the early 1970's. Region H indicates only one glacier with such a spike, Engabreen. Region I also has more negative net values in the late 1970's and again in the late 1990's.

The mean correlation for all glaciers within each of these Scandinavian regions (Table 3) is roughly similar to those calculated for the Alps. Again, the correlation for all glaciers within one region with a representative series derived from that region is stronger than that of a representative series from the adjacent region. For region H this value is 0.89 versus 0.56, for region I the value is 0.85 versus 0.68. Again, the correlations with a representative series from an adjacent region might be considered the lower bounds for the expected correlation that an actual net balance series for an unknown glacier would have with other glaciers of the region. All representative net balance series are depicted in Figure 10.

Considering all Scandinavian glaciers as a single unit and creating a representative series for that unit returned a mean correlation of 0.79 with the glaciers of region H, and 0.83 with the glaciers of region I. Both correlations are less than the correlations found using a representative series for each region individually, 0.89 (region H) and 0.85 (region I). This confirmed results found for the Alps that the representative series for each region is a better indication of within region temporal variation than is a representative series derived from all glaciers of the mountain system. However, the improvement of the individual region over the larger region, in this case, is fairly small. This latter point is especially relevant in the case of region I, South Scandinavia.

Temporal variation among the net balance of Scandinavian glaciers was much better represented by the derived climatic regions than it was by the entire system of 185 glaciers. Again, this is to be expected. The mean correlation value for glaciers in region H with the entire system is 0.36, mean correlation between the entire system and region I is a mere 0.28. Mean correlation between all mainland Scandinavia glaciers and the entire system is 0.34. In the case of Scandinavia, correlation with a representative series from all 185 glaciers is much lower than it is for the Alps. This is consistent with information found in the general literature suggesting that mass balance trends for Scandinavian glaciers have, until recently, remained more positive than most other glaciers (Ohmura, 2006). Over the period of record the glaciers in region H, North Scandinavia, had a net loss of roughly  $5.8 \text{ mm w.e. yr}^{-1}$  and region I, South Scandinavia, had a net loss of roughly  $6.8 \text{ mm w.e. yr}^{-1}$ .

### ***5.1.3 General Glacier Representation***

What is important about this particular method of region identification is the utility for identification of spatial regions exhibiting cohesive temporal trends in net mass balance. A number of authors have indicated that mass balance variations tend to be cohesive at hemispheric or even global scales especially when examined at longer time scales (e.g. Greene, 2005; Haeberli et al., 1999; Ohmura, 2006). The mean correlation value between the net mass balance time series of all 185 glaciers utilized in the DM05 dataset was a mere 0.04. This indicates the need for a robust method for identifying appropriate regional representative net balance series. Correlation amongst net balance series within the regions examined was much greater, generally above 0.70.

Regions of similar glacier behavior can be easily identified by direct analysis of correlation among net balance time-series of measured glaciers. However, this approach does not help identify which regional representative net balance series are most appropriately extrapolated to represent unmeasured glaciers. The climatic correlation method presented in this work utilized the theory that temporal variation of mass balance in glaciers is intimately linked to the temporal variation of surface temperature. Knowledge of the full extent of the region is a requisite component for the correct extrapolation of measured data to unmeasured glaciers. Through this review of glaciers within two of the most thoroughly studied glacier systems in the world the approach to region creation was tested, and proven capable of capturing a reasonably representative temporal evolution of regional mass balance in continental



Europe. It was also shown to be sensitive to small deviations in the patterns of temporal evolution for the sake of recognizing differences between adjacent regions that have been noted, yet sometimes ignored, by other authors. The approach utilized herein accounted for variation within net balance of measured glaciers and identified the full spatial extent of the regions within which the temporal evolution of net balance and surface temperature exhibited strong temporal correlation.

#### ***5.1.4 “Orphan” Regions***

Another notable feature of the correlation regions depicted in Figure 4, is the lack of any significant correlation region found over major portions of far Eastern and Western Russia as well as continental Canada. Because the original correlation surface was continuous, these regions were comprised of cells that were more strongly, or significantly, correlated with the temporal variations of non-adjacent regions. These regions may, however, contain glaciers in a climate with temperature trends similar to a geographically distant region. Such regions can be thought of as orphan regions because they are a cohesive grouping of correlated cells that do not contain a representative glacier. Because these cells are not more strongly or significantly correlated to an adjacent region the conclusion is drawn that the temporal patterns in temperature are different from that of adjacent regions. It follows that the temporal evolution of net mass balance would also be different than that of the adjacent regions. As such the adjacent regions do not contain appropriate proxies from which to derive an accurate temporal signal. However, the manner in which the regions of strongest correlation were defined allowed for the identification of the most

statistically significant “parent” region. This parent is the region to which the orphan shows the strongest, statistically significant correlation and is most likely to contain the glaciers an appropriate temporal evolution in the mass balance signal. Identifying the most appropriate parent region can be useful because models for glaciers in regions without representative glaciers (orphan regions) might be tuned using a representative glacier from the most appropriate parent region rather than an adjacent region which has less significant correlation.

Cogley and Adams (1998) estimated that roughly half of all small glaciers do not have a sufficient quantity of mass balance measurements nearby to estimate mass balance. The question of how to treat these has not yet been reliably answered. The climatic correlation analysis can be used to identify the best, or most likely, temporal signal for glaciers found within an unrepresented orphan region. Results of the climate correlation analysis suggest that temporal variations within each orphan region might be reasonably approximated by the temporal variation of the parent region, thereby helping to address the question of representation for roughly 80,000 glaciers. A more preferable means of identifying the temporal signal for the orphan regions is to institute or enhance direct observation programs within each of these orphan regions. This type of climatic correlation analysis provides additional rationale and motivation for enhancing the global glacier monitoring network in this manner.

## 5.2 NDCI

### 5.2.1 *Climatic Patterns*

Spatial patterns of temperature, evident in the TI (Figure 11) are found to be fairly homogenous. Spatial patterns of humidity in the HI (Figure 12) are found to be more spatially variable. These spatial patterns are generally consistent with patterns reported in the literature. The temperature index identifies Eastern Russia and Siberia as the most continental regions. The interior of Canadian North America and the Canadian Arctic Archipelago are also identified as strongly continental. Major parts of the Canadian Arctic are identified as continental yet Svalbard was noticeably less continental, a result similar to the report of Braithwaite (2005).

The temperature index and humidity index were merged to the NDCI surface and the pattern is very similar to that of the temperature index alone, however the manner in which the topographic nature of the continental area impacts the precipitation distribution becomes more evident (Figure 13). The pattern of continentality loses dominance where it is bisected by mountain ranges. The large majority of the space in the Northern Hemisphere exists near the mean NDCI value. However, a number of areas stand out for occupying the high (dry and continental) end of the NDCI scale. These high NDCI areas can be found off the North Coast of Alaska, the Canadian Arctic Archipelago stretching to the South tip of Ellesmere Island, Interior and Northeast Greenland, East of the Altai Mountains over the Gobi Dessert in Mongolia and the Central Plateau to the Eastern Highlands of Russia. The area over the Baffin Sea is an exception in the grouping of Canadian Arctic glaciers at the high end of the

NDCI. This geographic area is well known for being an unusual section of open water in the northern regions. There are also a number of areas of interest occupying the lowest (wet and continental) end of the NDCI scale. Characteristically low areas include the Southwest tip of Norway, Iceland, the Southern tip of Greenland, Southeast Alaska, and the West Coast of North America.

The HI and NDCI describe a very similar quantity of the variance in net balance deviations, although a cursory review of the two plots indicates the HI has a slightly smaller standard error. Despite the previous observations that the HI was a slightly better representation of net mass balance deviations for the 80 well studied glaciers, the NDCI is a better predictor of balance deviations for 185 at the hemispheric scale.

### ***5.2.2 NDCI Glacier Continuum***

The NDCI shows a striking linear relationship with deviations of the net mass balance time series (Figure 16). This helps to characterize the degree to which wet maritime glaciers have larger standard deviations and dry continental glaciers have smaller standard deviations following the principle component analysis logic identified by Letreguilly and Reynaud 1989; 1990). When attempting to identify the potential net balance time-series of an unmeasured glacier, the NDCI can be used to identify the extent to which a glacier is continental, and therefore the most likely value of net balance deviations from an extrapolated net balance series. This relationship was originally identified from the response of 80 independent glacier datasets from around the hemisphere. The addition of 105 lesser-studied glaciers indicates little change in the overall relationship and only marginally increases the slope of the regression

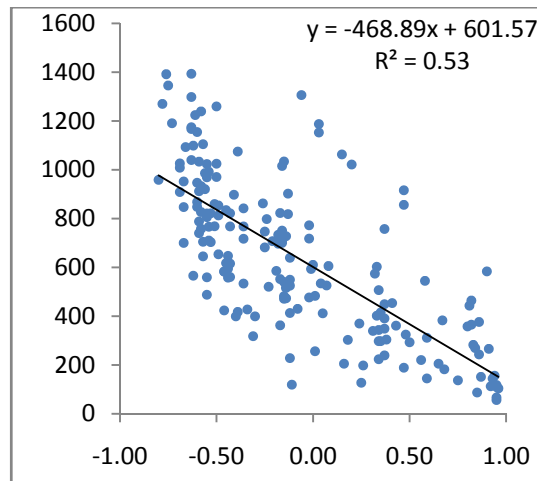
(Figure 17). The increased slope can be attributed to the increased number of wet maritime glaciers and their related larger net balance deviations.

The representation of glaciers in Table 4 matches well with the results of Meier (1984), Braithwaite and Zhang (1999), Dyurgerov and Meier (2005). Creation of the differenced index was done to define a numeric continuum upon which the individual glacier component of the mass balance can be represented. Identification of the NDCI value for a given glacier location, when compared to that of its measured peers, may be useful for identifying an appropriate range of glacier parameters and/or sensitivities for tuning mass balance models.

The  $R^2$  of the relationship between NDCI and net balance standard deviations is remarkably high despite the large range of deviations we find within well documented glacier systems such as the North Cascades, the Alps or Scandinavian systems. These systems have a large range of balance deviations at a single identified NDCI as a result of the spatial resolution of input data. Unfortunately a large number of glaciers are then represented by a single NDCI value, thereby reducing the overall strength of the relationship. These variations between glaciers in a given system are representative of the more detailed components of glacier situation, such as local variations in topography, slope, aspect and AAR. For example the North Cascades system consists of ten different glaciers with individual standard deviations ranging from 645 to 1105 mm w.e. Because of the spatial resolution of the ERA-40 dataset, all of the North Cascades glaciers are located in the same climatology grid cell, dictating that each has an identical NDCI value of +0.5. This relatively large variance in net balance is still

generally represented by the NDCI but indicative of the differences of local topography and glacier situation. A more detailed representation of climatic patterns utilizing an enhanced spatial resolution might more accurately represent those individual glacier variations.

For this reason a spatial interpolation algorithm was applied to the NDCI surface. The native resolution of the NDCI dictates that the value is determined by the  $2.5^\circ$  by  $2.5^\circ$  spatial grid of the input ERA-40 data. An attempt was made to artificially enhance spatial resolution of the NDCI grid through the application of a bilinear interpolation scheme to the NDCI surface. This basic interpolation method spatially distributes the NDCI values to create a smoothed NDCI surface dependent upon the value of surrounding cells. No new data is actually added, but the NDCI value for each glacier is based on the value of the cell the glacier resides in as well as the relative position of the glacier to the surrounding grid cell values. Using bilinear interpolation on the full set of 185 glaciers had little net effect on the slope and fit of the regression model. This result further strengthens the confidence we have in the regression (Figure 21).



**Figure 21. Standard deviations in mm w.e. of all 185 glaciers regressed with NDCI after application of bilinear interpolation of the NDCI value.**

### ***5.2.3 Indices Compared to Previous Work***

Analysis of NDCI identified a clear trend between the net mass balance standard deviations and the range of temperature amplitude and precipitation variability. This relationship has been qualitatively described by a number of authors, and quantitatively identified by in terms of a continentality index (de Woul and Hock, 2005) and amplitude or sensitivity. In order to determine the strength and validity of the NDCI parameter it was compared with other proxy measures of balance magnitude. Before comparing the NDCI with other published parameters, those parameters were evaluated using the same group of DM05 glaciers. Balance amplitude, published by Meier (1984), describes approximately 37% of the variance of the net mass balance standard deviations. Regional temperature and precipitation sensitivity, published by Oerlemans (2005), account for 43% and 41 % of the net mass balance standard deviations, respectively. The NDCI calculated for the full suite of

glaciers describes approximately 58% of the variance for mass balance standard deviations, a significant improvement on the balance amplitude and climate sensitivity variables. Additionally, the NDCI is found to describe approximately 55% of the variance in Meier's (1984) published balance amplitude and 56% and 52% of Oerlemans (2005) published temperature and precipitation sensitivity, respectively.

Of primary concern was whether or not a combined temperature and precipitation variable improved glacier representation over a simple continentality index. To address this, the individual indices for temperature and humidity were regressed with the published data (Table 5). In all cases the NDCI returned improved result over representation by the single parameter climate index. Furthermore, the interpolated NDCI, although not significantly better at representing simple standard deviations or balance amplitude, is notably better at representing published climate sensitivities of Oerlemans (2005).

**Table 5. Comparison  $R^2$  for NDCI, Indices and published amplitudes of Meier (1984) and sensitivities of Oerlemans (2005)**

	<b>NDCI</b>	<b>NDCI Interpolated</b>	<b>TI</b>	<b>HI</b>	<b>Net Balance Std Dev.</b>	<b>Net Balance Std. Error</b>
<b>NDCI</b>	1	0.95	0.91	0.85	0.54	0.01
<b>Amplitude (Meier, 1984)</b>	0.55	0.56	0.50	0.52	0.37	0.12
<b>T. Sensitivity (CT) (Oerlemans, 2005)</b>	0.56	0.62	0.54	0.50	0.43	0.00
<b>P. Sensitivity (PT) (Oerlemans, 2005)</b>	0.53	0.58	0.51	0.48	0.41	0.01

The strong relationship between NDCI and the balance amplitude term used by Meier (1984) indicated the NDCI is also a reasonable approximation of glacier sensitivity

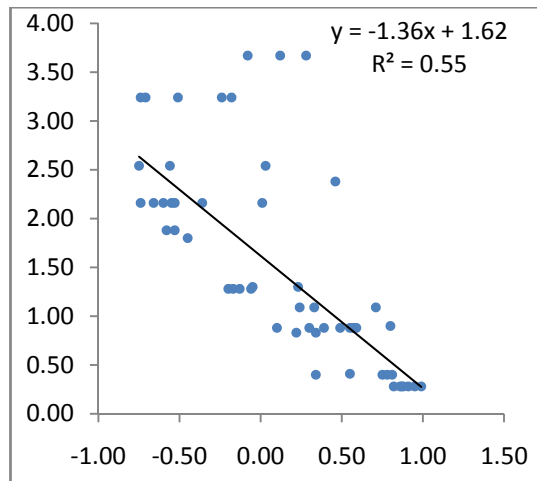


(Braithwaite and Zhang, 1999) Figure 22. The representation of balance amplitude by the NDCI works well,  $R^2 = 0.55$ , or 55% of variance explained. The relationship suffers for glaciers as a result of discrepancies in data for glaciers identified by Meier as the wettest glaciers, and with an amplitude  $> 3.24$ .

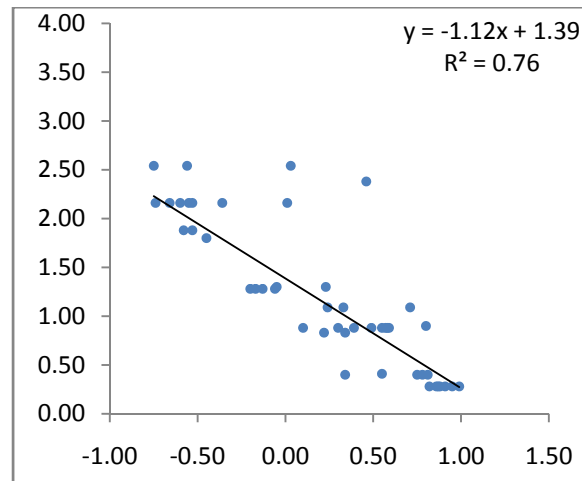
The ability for precipitation increases to compensate for mass loss due to temperature increases may not be adequately represented by the NDCI. In Figure 22, a number of glaciers exhibit larger balance amplitudes than the NDCI relationship would suggest. Removing these wettest glaciers improves the regression,  $R^2 = 0.76$  (Figure 23). For all glaciers with an amplitude  $< 2.5$  the relationship is strongest,  $R^2 = 0.88$  (Figure 24). These glaciers tend to be in area of high precipitation that generally falls in the winter season. It may be that the number of small discrepancies indicated by these high amplitude glaciers that are subject to large quantities of winter precipitation indicates a different characteristic relationship with climate. Physical characteristics of these glaciers are similar to glaciers found in the Alps and Scandinavia, but the glaciers of the North Cascades and Kamchatka are more maritime than the Alps and exist at lower latitudes than those in Scandinavia. The consistency of results within studies warrants further examination of this phenomenon, however it should be noted that mass balance data series for glaciers in Kamchatka are very limited, two glaciers with 5 years and one glacier with 25 years data. Additionally those glaciers in the North Cascades are not systematically measured for winter and summer balance suggesting the amplitude is calibrated from studies at South Cascade, Lemon Creek and Blue Glacier. Systematic biases in these datasets cannot be ruled out.

Further investigation of the discrepancies found at the wet/high amplitude portion of the continuum suggest that the glaciers Meier (1984) identifies as the wettest; those found on the Kamchatka Peninsula, Olympic Mountains and Coastal Rocky Mountains have a reduced NDCI as a result of relatively low HI values, rather than high TI values. However, Glaciers identified by Meier (1984) as maritime but slightly less wet, which are found in the North Cascades, were not listed as the wettest on the NDCI as a result of relatively low HI to TI ratio. It is not entirely clear if this is due to inappropriately low HI values, as in the previous case, or relatively high TI values. The lack of a consistent bias is one reason why the discrepancy may not be the result of errors in the NDCI process. The same discrepancy with respect to wet glaciers was a source of noise in the relationship between balance sensitivity and balance amplitude for glaciers listed as “Maritime” by Braithwaite and Zhang (1999).

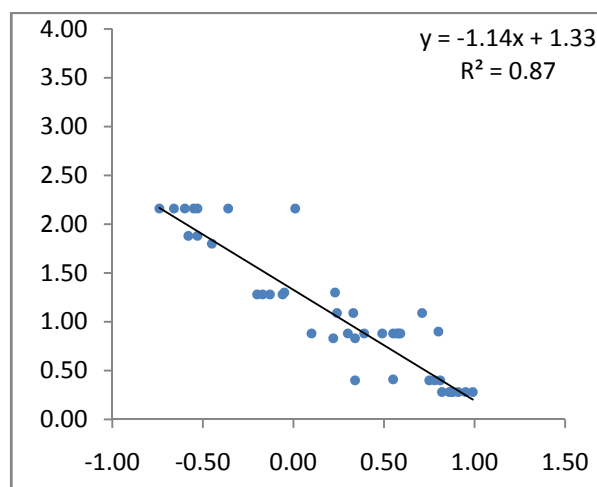
Wet, maritime glaciers may be responding to an additional significant, but unaccounted for variable. Alternatively, the inherently large standard deviations of maritime glaciers may make the amplitude factor more susceptible to significant seasonal balance anomalies. Oerlemans and Fortuin (1993) and Oerlemans (2005) identified maritime glaciers as having the fastest response time and being most sensitive to changes in temperature as a result of large balance gradients and large quantities of precipitation. This fact alone may make representation of variation within wet maritime glaciers more difficult especially when the representation relies on a driving variable such as temperature.



**Figure 22. NDCI vs Amplitude from Meier (1984) all glaciers.**



**Figure 23. NDCI vs Amplitude from Meier (1984) all but wettest glaciers.**



**Figure 24. NDCI vs Amplitude from Meier (1984) fewer wet glaciers.**

Evaluation the performance of the NDCI with balance sensitivities published by de Woul and Hock (2005) returns remarkably poor results. The NDCI describes only 8% and 36%, respectively, of the variation in temperature and precipitation sensitivity (Table 6). However, the de Woul and Hock (2005) sensitivities also do not agree well

with amplitude published by of Meier (1984). A more detailed look at the sensitivity of de Woul and Hock (2005) and suggests the precipitation sensitivity is more consistent with other proxies than the temperature sensitivity. The temperature sensitivity, in particular, does not match well with mass balance standard deviations. Interestingly the temperature sensitivity of de Woul and Hock (2005) exhibits an impressive relationship with mass balance standard error rather than Standard deviation (Table 7).

**Table 6. Cross comparison of  $R^2$  for published data (Meier, 1984; Oerlemans et al., 2005; de Woul and Hock, 2005)**

	<b>NDCI</b>	<b>Amplitude</b>	<b>CT (Oerlemans, 2005)</b>	<b>CP (Oerlemans, 2005)</b>	<b>T Sens dW &amp; H (2005)</b>	<b>P Sens dW &amp; H (2005)</b>
<b>NDCI</b>	1					
<b>Amplitude (Meier, 1984)</b>	0.55	1				
<b>CT Oerlemans (2005)</b>	0.56	0.59	1			
<b>CP Oerlemans (2005)</b>	0.53	0.62	0.97	1		
<b>T Sens dW &amp; H (2005)</b>	0.08	0.13	0.41	0.39	1	
<b>P Sens dW &amp; H (2005)</b>	0.36	0.22	0.10	0.14	0.26	1

**Table 7. NDCI  $R^2$  compared to published sensitivities of de Woul and Hock (2005)**

	<b>NDCI</b>	<b>NDCI Interpolated</b>	<b>TI</b>	<b>HI</b>	<b>Std dev.</b>	<b>Std. error</b>
<b>T Sens. (de Woul &amp; Hock, 2005)</b>	0.08	0.15	0.09	0.07	0.31	0.91
<b>P Sens. (de Woul &amp; Hock, 2005)</b>	0.36	0.38	0.36	0.27	0.56	0.30

The climate sensitivity to continentality curve published by de Woul and Hock (2005) assumes an exponential function, suggesting the mass balance amplitude becomes increasing more sensitive to changes in temperature as climate becomes more maritime. Braithwaite and Zhang (1999) also present an exponential function relating balance amplitude to sensitivity, although a cursory review of these data points reveals the curve of this function is strongly influenced by three data points from glaciers identified as “tropical”. The tropical glaciers exhibit an enhanced sensitivity to warming with relatively low balance amplitude. The results of de Woul and Hock (2005) when jointly considered with the errors identified in the NDCI representation of the wettest glaciers indicates that the glacier sensitivity continentality function may more likely be an exponential rather than linear relationship. However, Braithwaite (2005) evaluated Arctic glaciers only, and used a linear relationship to show the strong relationship between balance amplitude and mass balance standard deviations, which he describes as “more physically correct”. Analysis of NDCI utilizes linear regressions and does not use any glaciers identified as tropical. The nature of the relationship may indeed be more linear for Arctic glaciers that tend to be more continental in nature, but the inclusion of more humid maritime glaciers may require an exponential relationship. With the inclusion of more net balance datasets the nature of this relationship may become more clear.

Given the strong fit of the NDCI to published balance amplitude and glacier sensitivity the NDCI provides a fair assessment of individual glacier response to both temperature and precipitation. Review of the percent variance explained by the

temperature and humidity indices indicates that both variables can account for roughly half of the variability in mass balance datasets. In all cases, joint consideration of the TI and HI parameters as the NDCI enhances the representation of net mass balance standard deviations from individual glaciers, although improvements in the representation of precipitation may allow a more accurate representation of the wettest glaciers.

#### ***5.2.4 NDCI and the Question of Precipitation Representation***

Glacier volume change sensitivity is a function of precipitation. At maritime locations with lower temperature amplitudes, warming scenarios cause more precipitation to fall as rain rather than snow; which is manifest in an increased sensitivity (Oerlemans and Fortuin, 1992). Whereas glaciers in regions of high temperature amplitude are less sensitive to this phenomenon and able to sustain greater warming during the cool season before precipitation falls as rain rather than snow (de Woul and Hock, 2005). Regions with more precipitation have an increased sensitivity to temperature changes. This is why it was important to consider precipitation when attempting to represent glaciers based on sensitivity to temperature fluctuations. Considering this dependence on cold season precipitation, begs the question of whether the humidity parameter may have been better represented as a continuum of cold over warm season precipitation. Furthermore, would a more accurate representation of cold season precipitation more accurately represent the sensitivity of the most humid glaciers? The humidity index is presently designed as a measure of average precipitation deviations from the “global” mean, indifferent to season. This was done specifically to account for precipitation

that may fall as snow during the warm season. Of course this warm season snow is most likely to impact arctic glaciers, and the NDCI does presently represent those well. Creating a measure of seasonal precipitation amplitude, somewhat similar to our treatment of the temperature parameter, would have allowed for a ranking system based solely on cold season precipitation.

## CHAPTER 6 – CONCLUSION

Determining the realized or potential for sea-level rise is the culmination of many attempts to characterize glacier behavior. Attempts to identify this quantity have reliably produced results within one order of magnitude (Alley et al., 2005; Bindoff et al., 2007; Dyurgerov and Meier, 2005; Haeberli et al., 1999; Houghton et al., 2001; Meier, 1984). This task has been accomplished by extrapolation of data from roughly 300 measured glaciers to the nearly 160,000 ice masses referred to as small glaciers and ice sheets. Efforts to further constrain this quantity will require additional direct measurement of glaciers in the field as well as the application of physically detailed models to individual glaciers. In addition to the continuation of the important long-term glacier datasets that are presently available, further diversification of those glaciers being studied should be a priority. Deployment of measurement and modeling efforts should be targeted toward individual glaciers that represent the full range of variability found in the glacier system, and more specifically, glaciers identified as filling gaps in the continuum of important characteristics.

Unfortunately there are few measurable glacier parameters that represent measured variability at a reference glacier and can easily be related to an unmeasured glacier (Haeberli et al., 1999). Therefore, a representation method was implemented to determine the range of variability found among currently measured glaciers according to two important parameters, regionally coherent temperature variations and the degree of continentality, identified as being most responsible for variation in the net mass balance signal. The first parameter identifies a specific geographic region from



which a characteristic temporal evolution of the net balance signal that can be determined. The second characteristic identifies a more specific range of variability that might be expected of a given glacier based on the degree to which that glacier is considered continental. This approach linked measured glacier characteristics to climatology characteristics which can be used as a surrogate in locations where glaciers are not measured. This assists the goals of the WGI by enhancing the value of available glacier mass balance data by relating it to a readily available and consistently distributed proxy.

First glaciers were successfully classified into groups comprised of statistically significant correlation in the temporal evolution of gridded monthly temperature data from 1957 to 2002. This was done to identify regions of similar variability in the temporal evolution of annual net mass balance. With the knowledge of a regionally similar mass balance signal, annual balance in the regional sense, might then be determined from repeated observations at select glaciers with spans of several years (Haeberli, et al., 1999). Glacier net balance series within four regions of mainland Europe were tested for correlation. Within region correlation values are strong for 3 of the 4 regions, ranging between 0.67 and 0.73. Correlation within the fourth region, the West Alps, is weak relative to the others at 0.53. The relatively weak correlation values among glaciers in this region may be due to misrepresentation as a result of the spatial resolution of the input climate data or, more likely, interpreter error.

The likely misrepresentation identified in the Alps signifies a problem that is not likely to be prevalent among other correlation regions. Most regions identified in Figure 3

remained in their original form to the final representation of regions in Figure 4 and Table 2. The only exceptions occur in the Alps, Scandinavia and the Canadian Arctic Islands. These regions had nearly identical correlation contours and were manually aggregated to form a single region. The detailed analysis of the Alps and mainland Scandinavia indicated that this process may have introduced some error, although this error did not appear to introduce any overtly unreasonable assumptions. Fortunately the regions of the Canadian Arctic Islands are also fairly well studied; region M contains 7 balance series and region N includes 15 high quality balance series. Initial investigation indicates the original, non-aggregated, regions may have been more cohesive than the aggregated region and further investigation is recommended.

Investigation of glaciers found within the four regions identified for the Alps and mainland Scandinavia indicates the climate correlation method is sufficiently sensitive to small differences in regional patterns of temperature evolution. Differences in the regional mass balance profile of glaciers within each these regions were minimal, but were resolved. It may even be that the method employed is overly sensitive to these subtle variations. Mean correlation between net mass balance time series obtained by treating the Scandinavian and Alps regions as only two regions, rather than four, are still reasonably high; 0.52 for the Alps and 0.59 for Scandinavia.

“Orphan” regions comprised of a number of cohesive cells correlated with temporal evolution of temperature at non-adjacent “parent” regions were identified.

Identification of statistically significant parent regions for these orphans can only be accomplished through the use of some form of gridded climate data, as no reasonably

representative net balance data series exist within these regions. Any available mass balance series for glaciers within these regions should be tested for correlation with representative mass balance series from the parent regions to confirm correct representation. This method may provide a quantitatively robust approach to representation of the temporal evolution of annual net mass balance of the roughly 80,000 glaciers considered insufficiently proximate to a representative measured glacier.

Secondly, the NDCI was created using gridded climate data to rank glaciers on a scale of -1 to +1 according to both temperature variability and the relative magnitude of precipitation. The temperature and precipitation parameters were combined through a differencing method and the NDCI was used to identify a continuum of wet and humid to dry and continental glaciers which was found to be linearly related to net balance standard deviations.

Most importantly the continuum of glaciers identified by the NDCI was found to be more representative of sensitivity to warming than the standard representation of continentality which is based on temperature amplitude alone. The NDCI is used to accomplish this by adhering to the physical requirement that continental glaciers are more or less sensitive to changes in temperature as a function of the amount of precipitation received. Following this logic, the position of the glacier on the standard scale of continentality was moved more negative; the magnitude of the value reduced toward zero or increased toward -1, as a direct result of the amount of precipitation received at that cell location. The sign of the NDCI value alone allows determination

of the relative strength between the two parameters. The magnitude of the value identifies the specific ratio of one parameter to another. The position of the glacier relative to others on the scale serves as an indicator of the degree of glacier continentality relative to those positioned on either side of the glacier in question. In this manner the system can rank glaciers in a way that can be directly indexed to specific sensitivity data compiled from the number of on-going, physically detailed glacier modeling efforts. The range of possible characteristics of an unmeasured glacier can be constrained by its measured neighbors on the NDCI scale.

Using the regional classification and the NDCI unmeasured glacier can be represented by the two components most responsible for net balance variation. The net balance series can be represent, first by region, to determine the temporal evolution component of the mass balance series, then by NDCI derived continentality based on the glacier location, to determine the glacier specific component of the mass balance series. Certainly a mass balance series can, and whenever possible should, be further constrained through the use of additional physical data or detailed physically based models. In lieu of additional data this approach should provide reasonable representation of the potential range of glacier net mass balance.

Representing glacier characteristics in this manner leads to the potential for much future work. Most notably, the analyses should be carried out on a global scale and the ability to represent global glaciers should be tested. A more comprehensive examination of the geographic regions of glacier correlation is also needed. In this investigation, each geographic region contains at least one glacier with a multi-year

mass balance record. Any additional mass balance datasets should be used to further evaluate the consistency of the within-region temporal patterns. Similar gridded data products such as the NCEP/NCAR reanalysis or ERA-40 analyses with finer spatial resolution should also be examined and the results compared with those results presented here.

The NDCI should be evaluated with the inclusion of more maritime glaciers to better determine the effect of these wet glaciers on the relationships. Again, mass balance data from accurately modeled glaciers should be included to help further constrain the reliability and predictive power of the relationship. As mentioned in the discussion, the precipitation parameter might be considered in a manner that better represents the precipitation seasonality. Most importantly, the most extensive mass balance datasets should be used to calibrate the NDCI to specific balance amplitudes and climatic sensitivities. The accuracy of each of these approaches would benefit from the use of climatologies that have finer spatial resolution. While there are a number of ways to enhance the accuracy of these representations these approaches are not intended to be a substitute for detailed, more physically based models. The approach presented here has the benefit of simplicity while also accurately approximating the major components of mass balance variation at large scales. Moreover, this approach might be used to find those measured glaciers that might be *most* applicable for the sake of tuning the parameters of a more accurate and detailed mass balance model. Ultimately future research should establish clearly defined spatial extents for each glacier region in which member glaciers behave similarly. This would allow mass balance records

within a region to be interpolated to other, unmeasured glaciers and would provide key insights into changes in glacier mass and contributions to sea level rise.

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