Geomorphometric assessment of glacier state in the Karakoram, Himalaya

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Abstract—**The Karakoram Himalaya exhibits complex climate-glacier dynamics that operate within a mountain geodynamics framework. The region exhibits unusual positive mass balance and advancing glacier conditions, known as the Karakoram Anomaly. Unfortunately, climate, ablation and accumulation data are lacking for most glaciers to characterize various glacier states. Therefore, we evaluate process-morphology relationships over glacier surfaces for characterizing between surge-type and non-surge-type glaciers. We accomplish this by computing glacier profiles of geomorphometric parameters that are related to glacial dynamics and then perform wavelet analysis to extract spatial frequency signatures for glacier profiles and surfaces. We demonstrate that surge-type glaciers have steeper altitude profiles and more topographic shielding at high altitudes compared to non-surge-type glaciers due to potentially higher erosion rates and tectonism. One-dimensional wavelet analysis of glacier profiles reveals higher spatial frequency variation of topography on surge-type glaciers related to disequilibrium conditions and rapid ice and sediment fluxes. Large non-surge-type glaciers were found to exhibit larger scale periodic topographic variation related to downwasting patterns and supraglacial lakes. Finally, two-dimensional wavelet analysis highlights the anisotropic and periodic surge-related terrain features which provides the greatest discrimination between surge-type and non-surge-type glaciers.**

I. INTRODUCTION

The Karakoram Himalaya contains some of the world's most unique and complex glaciers (Fig. 1). Previous studies classify glaciers in this region based on glacier state, status or stage: surge-type, advancing, retreating and stable [1].

Surge-type glaciers are of particular interest to scientists because the mechanisms that promote surging are unclear. Glacier surge is the rapid advance of a glacier in a relatively short period of time. Surges typically occur when glacier mass accumulates to a certain critical level. During a surge, a large amount of glacier mass is redistributed from the reservoir area to the lower glacier [2]. Most temperate glaciers have overall negative mass balance under global climate change due to high ablation and insufficient ice-mass loading in the accumulation zone [3]. However, scientists have recognized that there are a large number of advancing glaciers including surge-type glaciers in the Karakoram [4]. Consequently, this region is referred to as the Karakoram Anomaly [5]. A large number of new surge-type glaciers have also been discovered [6]. For example, the Khurdopin glacier has surged several times since the late 1800s, with recent surges recorded in 1979 and 1999. Measured Khurdopin peak ice velocity is among the fastest rates globally for a mountain glacier [7]. Due to a paucity of climate, ablation, and debris cover data, it is difficult to ascertain each glacier's sensitivity to climate change and assess changing state conditions, as many glaciers oscillate over different timescales. We have yet to adequately characterize glacier state and be able to detect which glaciers are changing most rapidly.

Glacier surface processes and dynamics govern glacial topography. Therefore, geomorphometric parameters can be used to examine glacier morphometric properties related to ice and debris fluxes, as well as ablation dynamics. Techniques including Fourier and wavelet analysis can be used to examine the spatial periodicities in surface morphological conditions [8]. Wavelet analysis on topographic data has been applied generally for compression [9] and filtering of digital elevation models (DEMs) [10]. More advanced work to characterize glacier state and process regimes is still in its infancy.

The main objective of this study is to demonstrate unique glacier surface morphometric variation that is associated with climate-glacier dynamics and glacier state in the Karakoram Himalaya. Specifically, we evaluate the utility of wavelet analysis for characterizing spatial-frequency variation of geomorphometric parameters that help indicate glacier state or status.

II. Data and Methods

A. Study Area and Data

The Central Karakoram is located in northeastern Pakistan and exhibits extreme relief. We demonstrate our concept by studying four glaciers in this region (Fig.1). They are classified into two groups: stable non-surge-type glaciers (Baltoro and Hispar) and surge-type glaciers (Khurdopin and Momhil).

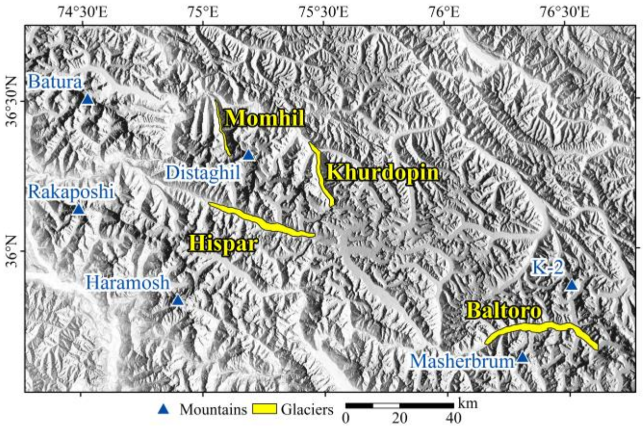

Figure 1. Study area in the Karakoram Himalaya. Glaciers examined in this study are highlighted in yellow and annotated (Baltoro and Hispar are stable glaciers, Khurdopin and Momhil are surge-type glaciers).

We use the Shuttle Radar Topography Mission (SRTM v3, 30m) digital elevation model [11] to generate geomorphometric parameters. Specific glacier outlines are extracted using the Global Land Ice Measurements from Space (GLIMS) dataset [12]. Glacial tributaries and non-glacial surfaces are removed from each glacier subset as we focus on producing profiles for the main trunk of a glacier. Satellite imagery further provides insight to supraglacial processes, including the presence of supraglacial lakes, crevasses and moraine distributions.

B. Glacier Profiles

Glacier profiles characterize morphological properties of the glacier surface at each altitude. Some geomorphometric parameters have great potential in characterizing glacier dynamics [13]. Consequently, we produce multiple geomorphometric parameter-altitude profiles.

Geomorphometric parameters used in this study include slope angle, skyview factor (positive openness of terrain), and convergence and divergence slope azimuth indices. The convergence index represents the degree to which surrounding terrain slopes towards the focus of a moving window, and the divergence index measures the degree to which the surrounding terrain slopes away from the focus. We utilize a 150 x 150 m moving window to calculate slope and slope azimuth indices. Each parameter is averaged in 10 meter altitude bins to generate a parameter-altitude profile for the glacier surface (Fig.2).

C. Wavelet Analysis

We use 1-D and 2-D continuous wavelet analysis to study the spatial frequency patterns of different glacier surfaces. Wavelet analysis characterizes the scale-dependent periodicity of a signal. Fourier analysis attempts to extract the same type of information but is inferior to wavelet analysis because, where Fourier analysis provides a frequency spectrum, wavelet analysis identifies where a certain frequency exists in the spatial domain. This is advantageous because we can then associate spatial frequency to certain locations and processes on the landscape.

We use the Continuous Wavelet Transform (CWT), as implemented in the Matlab Wavelet Toolbox [14], to extract spatial information from glacier convergence and divergence indices. Convergence and divergence characterize undulating topography caused by ablation dynamics and ice and sediment fluxes. The 2-D CWT is a space-scale representation of an image. A Cauchy wavelet was used as an anisotropic wavelet in the 2-D analysis to highlight directional topographic periodicities. We convert scale into spatial frequency to relate spatial frequency variation to certain process-form relationships on glacier surfaces. A wavelet coefficient image is the output of 1-D CWT, and the magnitude of the coefficients indicate how closely the data correlates with the mother-wavelet at a specific location along a transect. Smaller scales correspond to compressed wavelets (higher frequency) while larger scales correspond to stretched wavelets (lower frequency). Note that in this study, the output of CWT is converted from the raw 2-D complex number matrix to their absolute values and then represented as the percentage of energy (PE) in frequency-location space (Fig. 3a and 3b).

We define two indices that capture wavelet results from different perspectives. The maximum coefficient index (MCI) (Fig. 3c) is defined as:

$$MCI(f) = \max(PE(f)) \tag{1}$$

Where f is the spatial frequency. This index improves interpretability by simplifying the frequency magnitude information contained in the wavelet coefficient images.

To better evaluate the differences at the high frequency range, we define the high spatial-frequency index (HSFI) as:

$$HSFI(f) = \max(PE(x)) \cdot f_n \qquad (2)$$

where f_n is the normalized spatial frequency array. HSFI highlights and contrasts wavelet coefficients in the high frequency range because the term f_n gives greater weight to higher frequencies.

III. RESULTS AND DISCUSSION

A. Glacier Profiles

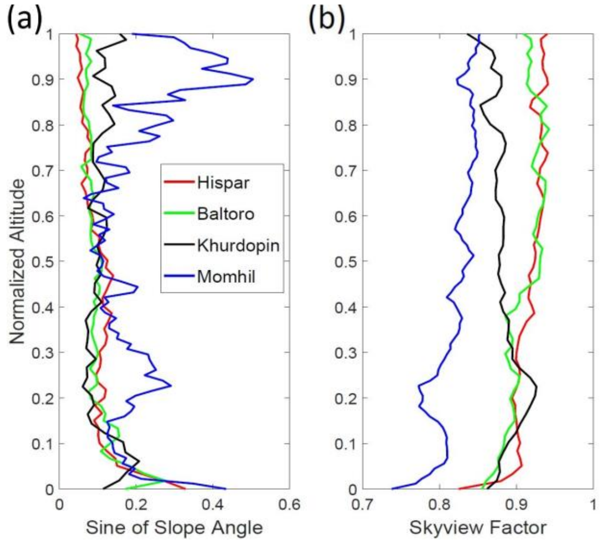

Figure 2. Glacier geomorphometric parameter-altitude profiles. (a) Sine of average slope angle. (b) Skyview factor. Parameter values are averaged over 10m altitude bins. Note the steeper slope and lower skyview factor of surge-type glaciers (black and blue) compared to stable glaciers (red and green) at high altitudes.

Stable large glaciers (Baltoro and Hispar) generally have low slope angles at high altitudes and higher slope angles at the terminus (Fig. 2a), which is due to relatively insufficient mass loading at accumulation zone and massive debris accumulation near the terminus. Downwasting also flatterns the stable glacier as many supraglacial ponds/lakes of various sizes are found at lower and mid Baltoro [15]. Surge-type glaciers (Khurdopin and Momhil), however, exhibit higher slope angles at high altitudes. The steeper slope in the accumulation zone is most likely related to tectonic uplift, as well as increased mass loading caused by orographic precipitation and avalanching. Similar slope profile was also observed on surge-type glaciers in Canada [16].

The surge-type glaciers have lower skyview factors compared to stable glaciers (Fig. 2b), indicating more topographic shielding at high altitudes. High topographic shielding is most likely related to the glacier erosional history that was related to the rapid and frequent surges of Khurdopin and Momhil glaciers.

B. 1-D Wavelet Analysis

Wavelet analysis enables us to examine the spatial frequency variations in the slope-azimuth convergence profiles (Fig. 3).

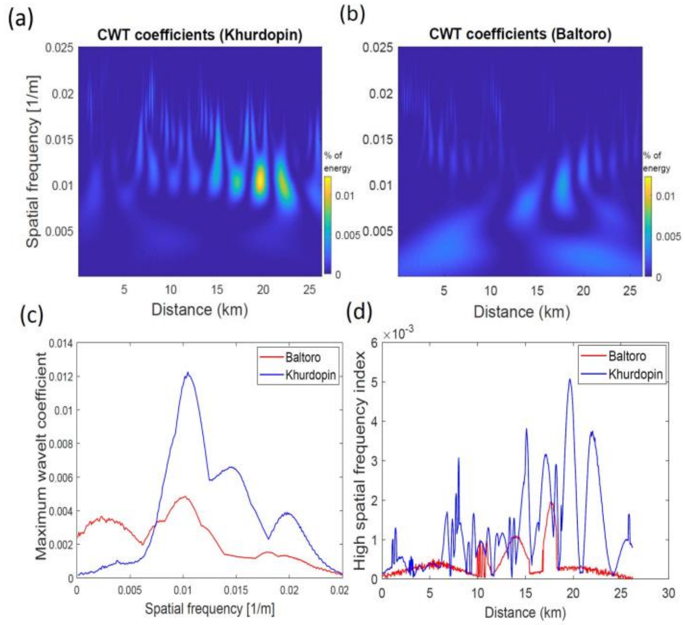

Figure 3. Wavelet analysis of convergence profiles down the flowline of glacier surfaces. (a) Wavelet coefficients for Khurdopin Glacier (percentage of energy in spatial frequency space). (b) Wavelet coefficients for Baltoro Glacier. (c) Maximum coefficient index for Khurdopin (blue) and Baltoro (red). (d) High spatial frequency index for Khurdopin (blue) and Baltoro (red).

The distribution and magnitude of wavelet coefficients in Figures 3a and 3b are significantly different. Khurdopin Glacier exhibits relatively high-frequency periodic convergence patterns at higher altitudes compared to the Baltoro Glacier. These variations are related to ice fracturing and disequilibrium conditions associated with glacial surge. The Baltoro Glacier shows lower frequency variations in convergence (Fig. 3c, 3d), which is most likely related to the unique downwasting patterns on a debris-covered glacier (e.g. supraglacial lakes, ice cliffs and glacier karst). Both glaciers exhibit low spatial frequencies in convergence near the terminus area (Fig. 3d), caused by reduced ice-flow velocities and increased debris-load accumulation at the terminus.

C. 2-D Wavelet Analysis

Two-dimensional CWT was computed using the divergence index for Khurdopin and Baltoro glaciers. The divergence index is useful for highlighting supraglacial moraines and crevasses.

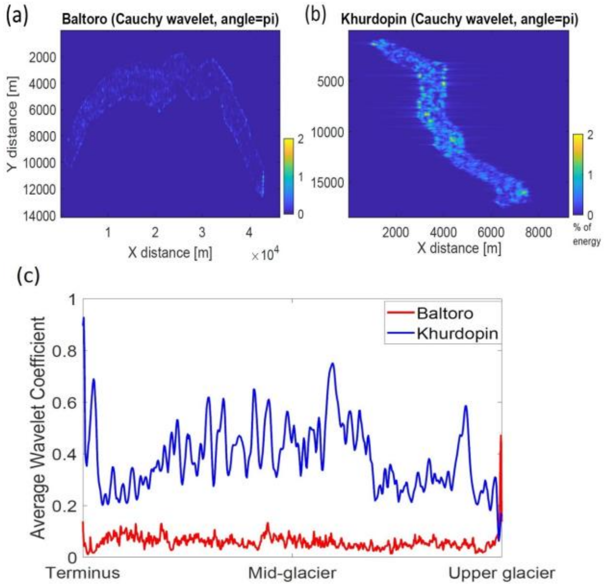

Figure 4. 2-D CWT results at a spatial frequency of 0.0083 m^{-1} in the E-W direction (angle = π) for Baltoro (a) and Khurdopin (b) glaciers using the Cauchy wavelet. (c) Averaged wavelet coefficient curve for Baltoro (red) and Khurdopin (blue) showing magnitude differences at the same direction.

Two-dimensional wavelet analysis results demonstrate that surge-type glaciers exhibit greater directional periodicities than non-surge-type glaciers (Fig. 4). We found that the surface of Khurdopin Glacier is highlighted by wavelet transform at certain angles, while Baltoro Glacier shows low values at all angles. This is because the anisotropic 2-D wavelet is very sensitive to the undulate moraines and widespread directional crevasses that are created by the rapid surge of Khurdopin Glacier [17]. This result demonstrates that 2-D wavelet analysis can be used to detect topographic anisotropy which is useful in identifying surge-type glaciers.

IV. CONCLUSIONS

Surge-type glaciers have steeper altitude profiles and more topographic shielding in the accumulation zone and exhibit higher frequency variation in surface convergence compared to non-surge-type glaciers in the Karakoram. Surge-type glaciers in the Karakoram can be identified based on surface slope-azimuth by highlighting anisotropic surge-related moraines and crevasses with 2-D wavelet analysis.

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