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Cross-references

Global Outlook of Snowcover, Sea Ice, and Glaciers

HYPSOMETRY

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Definition

Hypsometry describes the distribution of elevation of land with respect to sea level within an area of interest, with positive values being above sea level and negative values below sea level.

Quantifying hypsometry graphically

One approach to analyzing hypsometry is to produce a histogram of the frequency of different elevation bins. This simple approach requires a compromise between having bins that are too large such that insufficient detail can be extracted, and too small such that an underlying signal is obscured by noise. Alternatively, a graph of cumulative area (0–100%) with altitude can be plotted to show the relative proportion of a region at a specific elevation, known as the hypsometric curve. The elevations may be normalized relative to the range of elevations in the study area (value-minimum)/(maximum-minimum), and the area under this normalized curve is the hypsometric integral, which by definition lies between 0 and 1. The concept of a hypsometric curve has been widely used in geomorphological studies for many years to characterize drainage basins, with differently shaped hypsometric curves associated with different landscape forming processes and stages of landscape evolution. Hypsometry can be defined over a range of scales from a single drainage basin to the whole planet.

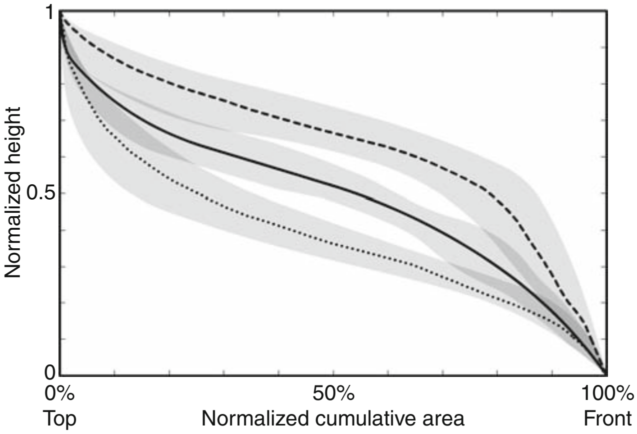
Glacier hypsometry

The same principle can be applied to the distribution of the area of an ice mass with altitude, that is, the glacier hypsometry. One of the first people to describe the hypsometry of glaciers and provide a typology for hypsometric curves was Ahlmann (in Lliboutry, 1956), who defined several types of curves: one for ice sheets, four types for valley glaciers, one for cirque glaciers, and one for piedmont glaciers. These classes were generated by manually calculating glacier areas based upon contour lines.

As an increasing amount of information on surface elevation has become available in digital form, for example from radar and laser altimetry, the construction of hypsometric curves has become more straightforward and they have been derived for many glaciers. One recent source of worldwide (60°N to 56°S) topographic information is the Shuttle Radar Topography Mission (SRTM), available at 90 m resolution outside the USA. This data set is the most recent detailed topographic information for many mountain regions with glaciers, for example, South America, the Himalayas.

Classifying glaciers by their hypsometric curves

From SRTM data, hypsometric curves for glaciers can be digitally derived. In order to classify these curves, they are compared to a theoretical linear hypsometry defined as a model. In this way, three main families of curves are obtained (Figure 1): glaciers with hypsometries above the model (dashed line), glaciers with similar distributions above and below the model (solid line), and glaciers with hypsometries below the model (dotted line). The first type of hypsometric curve (dashed lines) is typical of glaciers with large accumulation areas, located at plateaus surrounded by peaks, from where tongues flow down the valleys, that is, glaciers with predominantly high altitude areas (Figure 2). The second curve (solid line) is associated with glaciers that have similar widths from top to bottom, for example, those located on the flanks of cone-shaped volcanoes. The third curve (dotted line) is associated with piedmont glaciers or glaciers fed by more than one accumulation area whose tongues join at low altitude, yielding a large area at low altitude (Figure 2).



Hypsometry, Figure 1 Main types of hypsometric curves derived from Shuttle Radar Topography Mission (SRTM) data of tens of glaciers with a wide range of areas and types measured in Chile.

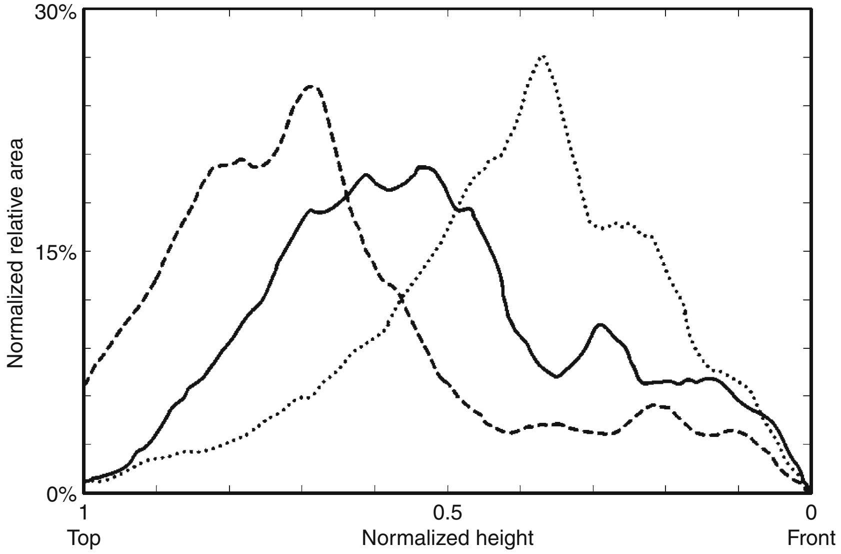
Relationship between hypsometric curve and Equilibrium Line Altitude

The above shapes reveal little about the glacier behavior if they are not analyzed together with the position of the Equilibrium Line Altitude (ELA) of each glacier within the hypsometric curve. Depending on the geometry of the glacier, a small change in the elevation of the ELA might result in a marked change in the areas of accumulation and ablation if a large portion of the glacier is at an elevation similar to the ELA. Conversely if there is only a small area at the ELA even a large change in its height may have little effect. Moreover, two glaciers with an identical ELA may exhibit very different behavior if one has a wide accumulation area with a narrow snout and another has a narrow upper basin and a broad tongue (Furbish and Andrews, 1984). By plotting the ELA on the hypsometric curve, the percentage area in the accumulation and ablation zones of the glacier can be easily calculated, and changes with time constructed. The derived ratio between the accumulation area and the total area of a glacier (accumulation area ratio) is one of the parameters often used to describe a glacier.

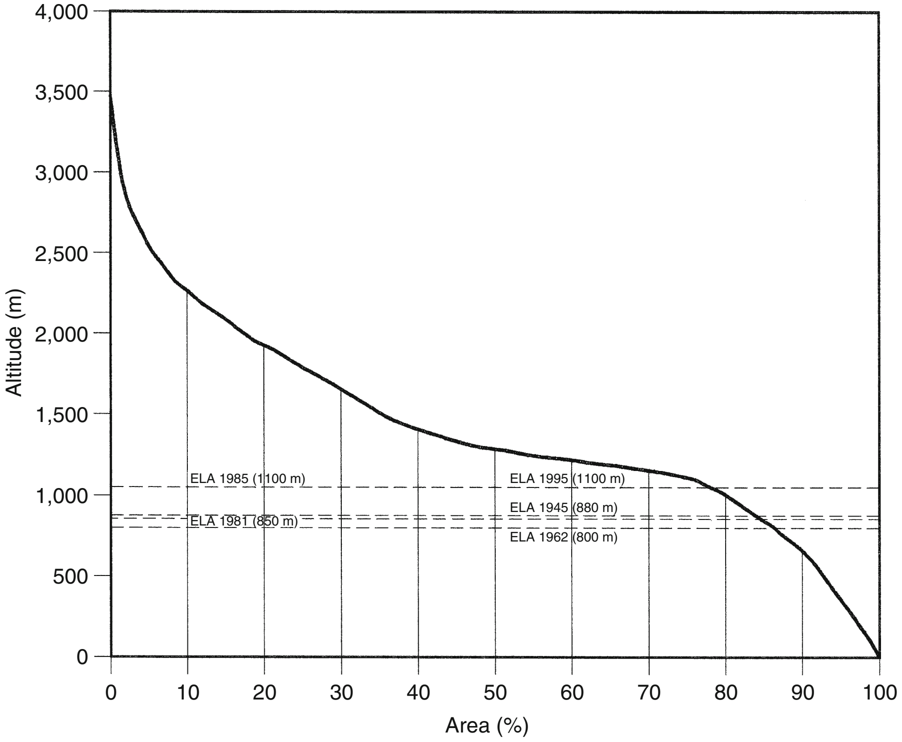
Examples of glacier hypsometric curves

Figure 3 illustrates the hypsometric curve for Pío XI glacier in the Southern Patagonian Icefields of Chile based on a digital terrain model derived from aerial photographs (Rivera and Casassa, 1999). This curve shows a steep slope for altitudes over 2,200 m and less than 1,000 m, indicating relatively small areas of land within these elevation bands. The majority of the Pío XI glacier lies at intermediate heights, especially in the 1,100–1,300 m region where the curve is much flatter (45.2% of the area of the glacier lies between 1,000 and 1,500 m). The ELAs from 5 dates, ranging from 800 m in 1962 to 1,100 m in 1995, are superimposed on the curve showing a general tendency for an increase in elevation over time. For much of this period, the ELA has been confined to the steeper section of the curve (below 1,100 m) so the change in area from accumulation to ablation zone has been small, with minimal impact on frontal behavior. This is one of the reasons why this glacier has been steady or even advancing in recent decades (Rignot et al., 2003). However, regional warming may in the future raise the ELA to a critical position, whereby a small further increase in the ELA may result in a significant loss of accumulation area, with a notable effect on the overall behavior of the glacier.

Comparing the behavior of the Upsala and Moreno Glaciers, also in the Southern Patagonian Icefields, further illustrates the importance of the position of the ELA with respect to the area-altitude distribution. The Upsala Glacier, where the ELA is located in a flat region of the hypsometric curve, has experienced significant retreat in recent decades, with a small increase in ELA due to



Hypsometry, Figure 2 Typical histograms for each main hypsometric curve.



Hypsometry, Figure 3 Hypsometric curve and Equilibrium Line Altitude changes for Pío XI Glacier, Chile (From Rivera and Casassa, 1999).

atmospheric warming resulting in a large decrease in the accumulation area. Moreno Glacier however, with a much steeper hypsometric curve, experienced only small variations in frontal position during the twentieth century and is thus relatively insensitive (up to now) to a rise in ELA (Naruse et al., 1995).

Similar results have been shown by studies on glaciers globally. Oerlemans (1992) illustrated how the large fluctuations, on the order of 4 km, in the front of Nigardsbreen in Norway can be attributed to relatively small climatic changes because of the glacier's geometry, with a narrow tongue fed by a large accumulation area which decreases markedly in size for a small increase in ELA. On Svalbard, Nuth et al. (2007) found that the glaciers of Prins Karls Forland, with a generally low hypsometric distribution, are generally downwasting, whereas those in Brøggerhalvøya and Oscar II Land with a higher hypsometric weighting are able to maintain their accumulation area.

Oerlemans et al. (1998) further demonstrated the importance of a glacier's hypsometry in understanding its response to climate change by modeling 12 glaciers and ice caps under different climate change scenarios. The authors found that no straightforward relationship between glacier size and fractional change of ice volume was apparent for any given climate scenario, which they attributed to the impact of the hypsometry of individual ice masses on their response.

Reconstructing past glacial conditions from hypsometric curves

The concept of hypsometry is also used to try and reconstruct past glacial limits from estimates of the ELA. Brozovic et al. (1997) postulate that during the Last Glacial Maximum, ELAs in the north-western Himalayan region could have been 600–1,000 m lower than at present, therefore, based on the geomorphological hypsometry, the area above the snowline would have been between 2 and 4 times greater than today, with many areas that are currently unglaciated being under a layer of ice. The hypsometry of glaciated regions can also be used to infer how rates of glacial erosion compare with those of tectonic uplift. Brozovic et al. (1997) showed that the hypsometries of glaciated landscapes around Nanga Parbat are correlated with the snowline elevation and independent of rates of rock uplift, thus indicating that glacial erosion rates can match, and exceed, uplift with climate dominating the evolution of the landscape.

Conclusion

By definition, hypsometry is a single statistic or curve which attempts to quantify a region, and this can be an effective way in which to assess the impact of glaciers on the landscape and their response to change. As concluded by Beedle et al. (2008), using accurate glacier outlines and hypsometries is essential for understanding glacier mass balance, volumetric change, the contribution of ice masses to sea level rise, and relationships between ice masses and climate. However, the hypsometric curve alone cannot explain ice dynamics, the impacts of volcanic activity, and the role of other localized features within individual basins, such as hanging valleys, narrow outlet gorges, or nunataks (rock outcrops surrounded by ice), all of which may also affect the behavior of a glacier. Thus, it is recommended by Brocklehurst and Whipple (2004) that hypsometry should not be used in isolation when assessing glaciers and glaciated landscapes.

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Cross-references

Equilibrium-Line Altitude (ELA)
Patagonia

HYSTERESIS

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Hysteresis is a phenomenon in which the response of a physical system to an external influence depends not only on the present magnitude of that influence, but also on the previous history of the system. Expressed mathematically, the response to the external influence is a doubled-valued function; one value applies when the influence is increasing, the other applies when the influence is decreasing. It is derived from the Greek word "husteros" which means slow, lagging behind or delayed.