ABSTRACT

The Earth’s topography results from dynamic interactions involving climate, tectonics, and surface processes. In this chapter our main interest is in describing and illustrating how satellite-derived DEMs (and other DEMs) can be used to derive information about glacier dynamical changes. Along with other data that document changes in glacier area, these approaches can provide useful measurements of, or constraints on glacier volume balance and—with a little more uncertainty related to the density of lost or gained volume—mass balance. Topics covered include: basics on DEM generation using stereo image data (whether airborne or spaceborne), the use of ground control points and available software packages, postprocessing, and DEM dataset fusion; DEM uncertainties and errors, including random errors and biases; various glacier applications including derivation of relevant geomorphometric parameters and modeling of topographic controls on radiation fields; and the important matters of glacier mapping, elevation change, and mass balance assessment. Altimetric data are increasingly important in glacier studies, yet challenges remain with availability of high-quality data, the current lack of standardization for methods for acquiring, processing, and representing digital elevation data, and the identification and quantification of DEM error and uncertainty.

5.1 INTRODUCTION

The Earth’s topography is the result of dynamic interactions involving climate, tectonics, and surface processes (Molnar and England 1990, Bishop et al. 2003). Numerous feedback mechanisms operate over unique spatiotemporal scales that govern hypsometry and terrain parameters. Similarly, the topography governs a variety of physical parameters and processes including stress fields, erosion and mass wasting, precipitation, sediment deposition, surface and groundwater flow direction and ponding, surface energy budget, and glaciation in a complex topographic feedback loop (Roe et al. 2002, Reiners et al. 2003, Arnold et al. 2006a). Scientists have long recognized the significance of topographic parameters for studying and modeling process mechanics, mapping the landscape, and detecting spatiotemporal change. Consequently, digital terrain modeling and the generation and analysis of terrain surface representations, commonly referred to as digital elevation models (DEMs) and geomorphometry, have become an important research topic for studying and solving problems in hydrology, geomorphology, and glaciology (Wilson and Gallant 2000).

Glaciological research indicates that glaciers in most areas around the world are receding (Burry 2006, Gardner et al. 2013). Internationally, scientists are attempting to inventory, monitor, and
understand current ice mass distributions and volume, glacier–climate interactions, glacier sensitivity to climate change, as well as assess the impact of glacier change related to water resources, natural hazards, and sea level fluctuations (Meier 1984, Dyurgerov and Meier 2000, Haeberli et al. 2000, Kaser 2001, Arendt et al. 2002, Huggel et al. 2002, Meier et al. 2003, Bishop et al. 2004, Kargel et al. 2005). With many high-altitude glacial lakes now forming in alpine areas (Huggel et al. 2002, Gardelle et al. 2011), with the threat of devastating landslides ever present and perhaps shifting (Kargel et al. 2010), with human habitation of risky places near glaciers rising (Kargel et al. 2011), and construction of valuable infrastructure increasing in alpine environments that never before had much human presence (Kargel et al. 2012), accurate DEM data are crucial for hazard assessments. This is especially true for glacier hazard-prone regions where field access is difficult due to severe terrain, political sensitivity, or financial constraints.

Glaciological research is increasingly utilizing remote-sensing studies and topographic information generated from airborne and satellite imaging, radar and LiDAR (light detection and ranging) systems, and GNSS (global navigation satellite system) surveying. Furthermore, DEMs are required for image orthorectification and radiometric calibration (Bishop et al. 2004), surface energy balance studies (Arnold et al. 2006a), debris-covered glacier mapping (Paul et al. 2004b), glacier ice volume loss and mass balance estimates (Berthier et al. 2007), and equilibrium line altitude estimation (Furbish and Andrews 1984, Leonard and Fountain 2003).

The mere availability of satellite imagery and DEMs, however, does not necessarily equate to accurate thematic information production and glacier parameter estimation (Raup et al. 2007). Consequently, researchers must account for a variety of issues in digital terrain modeling and geomorphometric analysis. Digital terrain modeling is a complex process that focuses on terrain surface representation schemes, acquisition of source data, terrain descriptors and sampling strategies, interpolation techniques and surface modeling, quality control and accuracy assessment, data management, and interpretation and applications (Wilson and Gallant 2000, Li et al. 2005, Fisher and Tate 2006). Accurate glacier assessment using topographic information is frequently an issue of DEM quality and methodological approach (Raup et al. 2007).

The purpose of this chapter is to address the topic of digital terrain modeling and geomorphometry for glacier assessment and mapping. Specifically, we consider numerous issues that must be effectively dealt with in order to estimate selected glacier parameters and delineate glacier boundaries. We first provide background information on digital terrain modeling to set the stage for DEM production using satellite imagery and methodological approaches. We then provide examples of analytical techniques that can be used to study glaciers.

5.2 BACKGROUND

Digital elevation models are digital representations of the Earth’s relief and are fundamental to many applications. The majority of currently available digital elevation datasets are the product of photogrammetric software, which exploits the technique of stereoscopy using overlapping image data, although increasing volumes of elevation data are also derived from radar interferometry and from laser altimetry. Additional elevation datasets are available from digitized map sheet topography and, although usually spatially limited, ground surveys. As with many remote-sensing exercises, the generation of digital elevation data represents a complex process involving image acquisition, computation and modeling, data management, and analysis. The terrain itself is spatially complex, and the need to represent it digitally and describe it quantitatively has led to various mathematical approaches for different scale and data constraints. Examples include the analysis of systematic high or low-frequency periodicity in altitude using Fourier analysis, and the identification of self-similar, spatially autocorrelated, and scale-dependent topography using fractal geometry and semivariograms.

Digital elevation data are normally represented in one of four ways, including use of: (1) a regular grid; (2) a triangulated irregular network (TIN); (3) contour lines; or (4) point profiles. Regularly gridded DEMs comprise square pixels of constant spatial resolution (the effective ground dimension) or constant latitude/longitude resolution, with each pixel assigned an elevation value, usually in meters and with respect to some datum (sea level or a higher order representation of the geoid). They are favored by geoscientists because they are directly comparable with remote-sensing imagery of equal spatial resolution, simple to analyze statis-
tically, computationally easy to represent, and can be saved in a range of formats (e.g., GeoTIFF, HDF). Conversely, they are poor at representing abrupt changes in elevation and heterogeneous topography, particularly at coarse resolutions, can generate large file sizes at fine resolution, and may have a large amount of data redundancy across flat areas. TINs represent topography using a mesh of adjacent, nonoverlapping triangles with each vertex assigned an elevation value. The TIN model stores topological information allowing proximity and adjacency analyses across a range of spatial scales. TINs usually require fewer data points than a DEM grid and are particularly useful for accurately representing extreme topographic features (e.g., channels and ridges) as well as for surface modeling (e.g., the calculation of slope, aspect, surface area and length, etc.). Contour maps, some digitized from paper topographic maps, provide more generalized representations of the terrain, but they are not so commonly used in glacial applications given the availability of contemporary DEMs for the entire globe; however, for the derivation of ice thickness changes over multiple decades, such digitized maps can be crucial. Lastly, point profile data normally represent elevations collected by laser altimetry (e.g., GLAS on board the ICESat), which illuminate a circular sampling area (footprint), the size and spacing of which is generally dependent on the altitude of the sensor. These data therefore tend to provide sparse coverage when acquired by satellite, and repeat pass data are not necessarily spatially coincident.

The terms DEM, DSM (digital surface model), and DTM (digital terrain model), are often used interchangeably to describe any digital representation of the Earth’s topography, but differ fundamentally in their inclusion or exclusion of surface cover in the data. DSMs can be thought of as including all elevation data recorded regardless of surficial cover; thus they represent tree canopy height across a forested area and building heights in the urban environment, for example. DTMs “strip out” such surface features and attempt to represent only the solid Earth, which can be a challenging task (sometimes requiring large amounts of interpolation) where dense ground cover(s) exist. The term DEM is used more generally to describe an elevation dataset without specifying the elevation reference (e.g., solid Earth, surface cover, subsurface topography). Many satellite-derived elevation datasets are of insufficient vertical resolution to require an explicit declaration of whether they include surface cover or not, and are therefore generally referred to simply as DEMs.

The use of elevation data derived from remotely sensed imagery has a number of advantages over alternative sources. First, the range of sensors available for producing DEMs offers flexibility in scale. Many medium-resolution (10–30 m) satellite sensors (e.g., ASTER, ERS-1/2) are able to provide stereoscopic imagery for DEMs of wide areal coverage, while local to catchment-scale DEMs can be derived from an increasing number of fine resolution (1–10 m) sensors (e.g., SPOT 5 HRS, Quickbird, GeoEye) or aerial imagery. Normally, the scale of the topographic variability to be modeled informs the selection of the source imagery (see Section 5.3.1). Second, many glacierized areas of the world are inaccessible for logistical or political reasons, so for the inclusion of three-dimensional data in global databases such as GLIMS, remotely sensed elevation information provides the only option. Third, as historical archives of these data are accumulating, the opportunity to conduct multitemporal (and thus dynamical) studies becomes possible. Fourth, and finally, the increasing availability of no-cost data derived from remotely sensed sources opens up the discipline of cryospheric remote sensing to all interested parties, which can only ultimately advance scientific understanding at a greater pace.

In relation to this last point, however, it is important that standards and procedures for DEM generation and analysis are available for scientists worldwide, an issue that is discussed later in this chapter (p. 137). In brief, the utility of a DEM is dependent upon a certain level of expertise from the operator to ensure the correct scale of representation, accurate characterization of terrain parameters, and overall planimetric and vertical accuracy. For example, a major difficulty in using digital photogrammetry to generate elevation data over glacier surfaces is that accurate DEMs can only be derived if the glacier surface shows sufficient topographic and/or radiometric heterogeneity to correlate image pairs (Favey et al. 1999), which otherwise can result in grossly inaccurate elevation estimates over some large expanses of bare ice and/or snow. Image saturation or low dynamic numbers in deeply shadowed areas also result in either null values or erroneous elevations. Consequently, great care is required to ensure that the data selected for an application are appropriate, processing is carried out with a high level of expertise, and errors in any derived data are accurately reported, so that real
5.3 DIGITAL ELEVATION MODEL GENERATION

5.3.1 Source data

Topographic maps exist for every country, and these can be utilized to generate a DEM, provided the map is of sufficient quality for the intended application. In developing countries, issues of cartographic scale, map coverage, quality, and availability may be problematic. In some countries the maps are military secrets, or have been degraded in quality given the scale, contour interval, or introduction of error (e.g., Soviet topographic 1:50,000 map series of Afghanistan). If suitable maps exist DEMs can be generated by cartographic digitization using techniques such as line-following digitization or raster scanning.

High-resolution aerial and satellite images are also effective ways to generate and update topographic information. Digital elevation models can be derived using stereo (overlapping) pairs and photogrammetric techniques, which depend on knowledge of the exact image and terrain geometries at the time of acquisition. Numerous investigators have reported on the generation of DEMs from aerial photography and a multitude of satellite-imaging systems including ASTER, IRS, and SPOT for glaciological applications (Kääb 2002, Berthier and Toutin 2008). Although satellite imagery is generally available, aerial photography is more difficult to acquire for many glacierized regions of the world (e.g., Karakoram) because of political sensitivities and poor archiving, and some air photos are expensive (e.g., Alaska), which can limit historical analyses. However, the demilitarization of Corona satellite imagery provides historical data for many regions of the world at relatively fine (<10 m) spatial resolution; Corona also provides stereo coverage facilitating photogrammetric analyses (Surazakov et al. 2007, Bolch et al. 2008).

For cryospheric applications, and especially useful for three-dimensional information, ASTER is one of the most appropriate and accessible sensors available for several reasons. First, and most importantly, the coupled nadir and backward-looking sensor systems in the near-infrared enables fine-resolution and routine along-track stereoscopic vision (Fig. 5.1). Second, the spatial resolution of these stereoscopic data (15 m) provides the perfect balance between image detail and wide swath width (60 km) that is required for regional-scale glacier

![Figure 5.1](image-url). Imaging geometry of the ASTER sensor, on board the Terra satellite, launched in December 1999. The satellite is in a 705 km, Sun-synchronous orbit that results in a 16-day revisit period for any given location on Earth. The ASTER sensor is equipped with two bands in the near-infrared: one at nadir (3N) and one backward looking (3B). It takes the sensor approximately one minute to cover the same area of ground with both sensors, thus yielding a stereo pair of 60 km swath from which DEMs can be extracted (adapted from Hirano et al., 2003).
studies. Third, the adjustable sensor gain settings provide increased contrast over bare ice and snow, which is critical for the derivation of accurate elevation data using photogrammetric techniques. Fourth, the relatively short revisit period of the sensor (16 days for nadir viewing or 2 days for off-nadir pointing) provides high-intensity coverage in cases of natural disaster emergencies or other special needs; in more routine cases, the short revisit time provides many chances to acquire a cloud-free image of an area of interest, even in notoriously cloudy areas. ASTER data are routinely used to provide DEMs for the derivation of three-dimensional glacier parameters for all glacierized regions, and are available at no cost to regional centers involved in the GLIMS project. However, the actual performance of ASTER has resulted in far less frequent data acquisitions and often sub-optimal sensor gain settings than the observation plan calls for, thus reducing the system’s value from what it could be.

Images acquired by synthetic aperture radar (SAR) contain information relating to both the magnitude and phase of the backscatter signal, both of which are useful for deriving DEMs. Radargrammetry exploits the magnitude element of the return signal. Similar to photogrammetry, radargrammetry makes use of two spatially separated backscatter images to form a stereo model of the terrain (Toutin et al. 2013), with the exact image geometry being supplied by increasingly accurate orbital data records (Scharroo and Visser 1998). Interferometric SAR (InSAR) makes use of the phase element of radar return. The phase difference between two independent return signals is very sensitive to topographic variations (as well as any surface displacements between image acquisitions) and can be “unwrapped” to derive a digital terrain surface, often with very high accuracy. DEMs over glacierized terrain have been successfully derived using a range of SAR image sources including ERS-1/2 (Eldhuset et al. 2003), Radarsat (Peng et al. 2005), and sensors on board fixed wing aircraft (Muskett et al. 2003). The preceding chapter by Kääb et al. has a detailed treatment of various methodologies and glacier applications using radar data.

Airborne laser scanning systems are an important operational tool for generating high-resolution topographic information. Numerous researchers have utilized and evaluated DEMs generated from LiDAR data for glaciological applications (Rees and Arnold 2007). Pulses of electromagnetic energy interact with surface materials to regulate the intensity of the returning signal. A LiDAR system produces data that may be characterized as a 3D point cloud, which must be processed to remove erroneous measurements relating to reflectance from clouds, smoke, or birds, for example (Arnold et al. 2006b). Consequently, filtering, classification, and modeling are required to generate a DEM from laser-based measurements. The high quality of LiDAR-based DEMs permits improved geomorphometric characterization of the terrain and glacier surfaces, which translates into improved assessment and modeling of a variety of processes.

Finally, Global Navigation Satellite Systems (GNSS) can be used for direct measurement of the Earth’s surface topography, and are increasingly replacing the use of traditional theodolites and total stations. Earth scientists are routinely utilizing GPS receivers on a variety of platforms to collect point and profile measurements for terrain and glacier surface representation (Miller and Pelto 2003). Differential GPS (dGPS) refers to calculation of an accurate roving receiver position with respect to a reference station and can yield accuracies as fine as 10 mm when the differential phase of multiple satellite signals is exploited. This method is particularly relevant for the collection of ground control data as input to DEM generation.

5.3.2 Aerial and satellite image stereoscopy

The process of deriving elevation data by photogrammetric techniques is well established and widely documented (Kääb et al. 1997, Kääb and Funk 1999). Deriving elevation data from stereo photographs relies on recreating the geometry between sensor and terrain at the exact time of image acquisition. The user supplies approximate data relating to the aircraft location and the average terrain height above sea level in addition to accurate statistics on the camera geometry and image dimensions. The software applies least-squares regression to reduce errors in the approximations and arrives at a stereo model that realistically represents the real-life situation at the time of image acquisition. The least-squares adjustment algorithm is used to estimate the unknown parameters associated with a solution while also minimizing error within the solution. This is regarded as one of the most accurate techniques to:
estimate or adjust the values associated with exterior orientation (sensor positioning and view direction at time of image acquisition); estimate the $X$, $Y$, and $Z$ coordinates associated with tie points; estimate or adjust the values associated with interior orientation (sensor geometry, including focal length); and minimize and distribute data error—introduced by ground control point (GCP) coordinates, tie point locations, and camera information—through the network of observations (list modified from Leica Helava 2004).

The least-squares algorithm processes the data iteratively until the errors associated with the input data are minimized. These errors are measured in terms of residuals (the degree to which the observations deviate from the functional model). Residual values (the distance between calculated statistics and user input values) are summarized by the root mean square error (RMSE), which should ideally be less than twice the pixel size of the imagery for the resultant orthoimages and elevation information to be considered accurate when compared with the actual terrain properties.

Once the error is within thresholds considered satisfactory by the user, the DEM is extracted by the generation of spatial rays from the first image that intersect in three dimensions with the corresponding points on the second image (identified by image-matching algorithms), thus giving a height value for each modeled pixel (Fig. 5.2). Elevation is determined by measuring shifts in the $x$-direction ($x$ parallax) of the rectified images. The exact process followed in DEM generation may differ slightly depending on the software employed (see Section 5.3.4) but typically follows a series of key stages (Fig. 5.3).

### 5.3.3 Ground control points

Ground control data may be derived by traditional surveying techniques (such as triangulation, trilateration, traversing, and leveling), contemporary survey techniques (such as dGPS measurement and
laser ranging), and/or the identification of clearly defined features (e.g., mountain peaks and road intersections) on large-scale map sheets. They may give information on horizontal positioning, height, or both. Collectively, ground control data inform the stereo model of the spatial position and orientation of a photograph or satellite image relative to the ground at the time of exposure (or scanning), and their quality is important to the accuracy of derived elevation data. As a minimum, the accuracy and precision of any ground control data should be twice that of the expected DEM to avoid adversely affecting the derived data. Research has shown that the accuracy, number, and distribution of ground control points used in the iterative least-squares adjustment to refine the geometric model can also impact DEM accuracy significantly (Toutin 2008). While three GCPs are theoretically sufficient to compute a stereo model from frame imagery (Gonçalves and Oliveira 2004), the minimum number for other sensors depends on the sensor model employed and the number of unknowns in it. A larger number than the minimally required is usually employed to ensure redundancy in least-squares adjustment, to reduce the impact of map and plotting errors, and to facilitate post-derivation accuracy tests (Toutin 2002). On the other hand, where GCPs are known to have low accuracy it is beneficial to limit the number used in the adjustment to avoid errors propagating through to the output DEM.

In addition to the quality of any ground control data used in a stereo model, the theoretical accuracy of a DEM is also dependent on the base-to-height ratio of the system and the quality of the image matching used to refine the stereo model. If no ground control data are available, only relative DEMs may be derived (where horizontal and vertical values are only known relative to an arbitrary datum). Their accuracy is thus dependent only on sensor characteristics and the success of image matching. Further parameters that can influence the accuracy of any derived elevation data include the quality of geometric and radiometric image calibrations (which also impact matching success and ground control point identification) and the quality of sensor ephemeris and attitude data that is entered into the stereo model. Check points, which are most often surplus ground control data, can be used to quantify DEM errors but, similarly, the quality of accuracy assessment is only as good as that of the checkpoints used.
5.3.4 Software packages

In addition to the software used by NASA and the Japanese Aerospace Exploration Agency (JAXA) for the operational generation of ASTER DEMs, there are four university or private software packages, as well as five commercial off-the-shelf (COTS) software modules for processing stereo ASTER data to generate DEMs (Toutin 2008). We now give a brief description of some of the main software packages available.

The Geomatica® OrthoEngine SE of PCI Geomatics (www.pcigeomatics.com), adapted to ASTER stereo data, was developed in 1999 under USGS contract with the collaboration of the Canada Centre for Remote Sensing, Natural Resources Canada, for mathematical, 3D modeling, and algorithmic aspects. It may be the most-used software for performing 3D sensor orientation and DEM and orthoimage generation. Both relative DEMs without GCPs and absolute DEMs with GCPs can be generated while an existing DEM can be added in the processing. The accuracies obtained in different research studies were similar to those obtained at USGS: horizontal and vertical accuracy of ±15 m and ±20 m (1σ) respectively, depending on GCPs, study site, and relief.

The LPS photogrammetric software suite from ERDAS (http://www.erdas.com) includes ASTER-specific data import, radiometric correction, and sensor model functions. It uses a feature-based, automatic terrain-adaptive, hierarchical image-matching scheme for automatic DEM extraction and can output grid, TIN, and point cloud data. Of the software described here, LPS provides the most comprehensive control over the DEM extraction and editing process. A number of automatic spike and blunder detection algorithms aid the detection of local extraction errors, and automatic blending and smoothing around the perimeter of area edits leads to seamless data continuation through interpolated or replaced values. The most promising of these algorithms fuses independent datasets to achieve a complete DEM; in one approach, Crippen (2010 and unpublished results) used parallax–elevation cross-correlation as a means of detecting artifacts in the ASTER DEM so as to determine where replacement with other data (e.g., from SRTM) should be done.

The AsterDTM module, developed by SulSoft, the exclusive ENVI distributor in Brazil, was added to ENVI as an add-on module in 2004 (http://www.ittvis.com). The software can create DEMs from ASTER Level 1A and 1B stereo pairs with the aid of orbit/sensor modeling, quasi-epipolar image generation, cross-correlation matching, and automatic detection of water bodies. An existing DEM can be added to fill in low-correlation areas. The claimed accuracy by ENVI for a relative DEM without GCPs is better than ±20 m and for an absolute DEM with GCPs ±30 m in planimetry and ±15 m in elevation (all with 90% confidence interval). These results were confirmed by end users generating DEMs from Level 1A stereo pairs both with and without GCPs, and from Level 1B stereo pairs without GCPs.

The Desktop Mapping System Softcopy®, Version 5.0 is designed to run under the Microsoft® Windows® XP Professional operating system and provides a complete two-dimensional and three-dimensional photogrammetric mapping capability using scanned aerial photographs or digital images recorded by airborne or satellite sensor systems. Experiments with stereo ASTER data over different mountainous study sites achieved RMS errors of about ±15–25 m (1σ), showing equivalent results to those derived by USGS (see PCI). DMS Softcopy 5.0 retains the speed, functionality, and ease of use of earlier versions of the DMS software, but has been streamlined to allow for even faster, more efficient implementation of operations.

SilcAst, produced by Sensor Information Laboratory Corp. Japan (www.silc.co.jp) and exclusively developed for ASTER, is written in IDLR6.1 and can be executed with IDL VM without an IDL license. The main functions are digital elevation extraction either from Level 1A and Level 1B imagery, water body identification, orthorectification, and Level 1B data generation, but the software does not accept GCPs. ASTER 3D data products are provided as Standard (fully automatic) with potential miscalculated elevations, and High (semi-automatic) with interactively corrected miscalculated elevations. In 2009, SILC with SilcAst produced a high-quality global DEM (G-DEM1; see Section 5.3.6) from ASTER data acquired within an 83° latitudinal limit. Covering all the land on Earth, it is freely available to all users in 1 × 1° grid tiles in latitude and longitude. While the ASTER G-DEM1 contains 30 m grid spacing with ±7 m accuracy (1σ), recent scientific studies demonstrated some high-frequency errors (appearing within tile grids as pits, bumps, “mole runs”, and other residuals and artifacts), requiring down-sampling to 90 m spacing.
5.3.5 Postprocessing (interpolation and smoothing)

DEM generation often requires the interpolation of elevation values between available sample points, particularly when contour maps or satellite imagery are the source data. Consequently, various approaches for how to interpolate this calculated (not measured) elevation in the DEM production process have been developed. The choice of approach depends mainly on relief within the imagery, the type of information that will be derived from the DEM, and the proposed application (Rasemann et al. 2004). Interpolation accuracy depends on interpolation algorithm type, surface characteristics, and the distance between sample points (Kubik and Botman 1976). There is a paucity of quantitative evaluation of interpolation accuracy over glacierized terrain and, of the few studies that do exist, only a handful have employed ground data to make the assessment (Cogley and Jung-Rothenhausler 2004). At present, uncertainties in DEM accuracy do exist depending on the choice of the interpolation algorithm employed; therefore, all qualitative and, in particular, quantitative results from glaciological analyses that include DEMs must be interpreted with caution.

Some of the interpolation methods that have been used in glacier research include (but are not limited to) Triangular Irregular Network (TIN; Gratton et al. 1990); Inverse Distance Weighted (IDW; Etzelmüller and Björnsson 2000); spline (Mennis and Fountain 2001, Bolch et al. 2005); and kriging (Burrough and McDonnell 1998).

**Triangulation:** since this method produces individual triangles with constant exposition and aspect rather than a continuous relief, the final DEM is not differentiable. To ensure that information on curvature can be extracted, the DEM has to be converted to a grid. Problems occur at sharp edges, deep valleys, and cliffs. Often, valleys and ridges show a typical “terracing” effect. Such artifacts can be eliminated by manually adding elevation information, by using structural information with elevation values (Heitinger and Kager 1999, Rickenbacher 1998), or by subdividing the triangles (Schneider 1998).

**Inverse Distance Weighted:** a relatively simple algorithm that weights the sample point value according to its distance from the pixel of interest. The weighting and number of sample points have a strong influence on DEM quality. For example, a strong weighting based on only few sample locations produces a rough surface in which the sample points themselves are heavily emphasized.

**Spline:** this interpolation method applies a special function that is defined step by step by piecewise polynomials that are continuously differentiable. Most common in DEM generation are low-order cubic \((r = 3)\) and bicubic \((r = 2)\) splines. In general, the surface of the final DEM is smooth and even. However, the main problem is the occurrence of overshoots (i.e., unnatural “holes” and “spikes”). To prevent such overshoots, a regularized spline-with-tension algorithm is used (Mitasaova and Mitas 1993). This method uses a function that specifies how fast the collection of sample points decreases with increasing distance thereby attenuating the magnitude of overshoots.

**Kriging:** a geostatistical method, based on a stochastic model, which predicts the elevation at a specific location and is particularly used when a trend (here: the spatial correlation of elevation values) exists. One disadvantage of this method is that adjustment of the semivariogram model to the existing data structure requires experience.

Various studies have considered the relative accuracy and appropriateness of each of the above approaches. For example, Kamp et al. (2005) tested three interpolation methods—\(\text{IDW} \), spline, and \(\text{TIN}\)—when generating a DEM from 1:50,000 topographical maps of Cerro Sillahuay in the Andes of Bolivia and Chile using Esri ArcGIS 3.2 software. In this study, both \(\text{IDW} \) and spline methods produced very good results in high relief areas, but a large number of artifacts in generally flat terrain. The authors concluded that both algorithms had problems handling larger distances between contour lines. Instead, the most accurate DEM was generated using the \(\text{TIN}\) method, although a first raw DEM contained many artifacts—mainly over flat terrain, caused by the triangles that are used by the \(\text{TIN}\) method for interpolation.

Tests similar to those made by Kamp et al. (2005) were described by Racoviteanu et al. (2007) for the Cordillera Ampato (southern Peru). In this study, the examination of RMSEz (vertical error) values for DEMs derived from topographic data (1:50,000 maps constructed from 1955 aerial photography) revealed that no interpolation method performed
perfectly. While the IDW DEM and TIN DEM showed accuracies of only 21 m and 24 m, respectively, the spline (here: TOPOGRID) DEM produced a vertical accuracy of ~15 m, outperforming the other available algorithms. However, the authors noted that all three DEMs produced “terracing” effects, an artifact of preferential sampling along the contour lines, with points closer to the contour lines being interpolated using the same elevation values. The terracing effect was most severe using the IDW interpolator. Similar terracing artifacts were described by Etzelmüller and Björnsson (2000) using the same interpolator, and by Mennis and Fountain (2001) using the spline-with-tension interpolator. Wilson and Gallant (2000) showed that such terracing artifacts affect calculations of topographic characteristics such as slope, aspect, and profile curvature.

DEM’s constructed over largely featureless terrain often fail to characterize subtle (or even abrupt) changes in surface topography, which can be rectified by the use of breaklines. Breaklines are linear features that describe interruptions in surface smoothness and are typically used to define channels or ridges, for example, where there is a clear change in surface topography. However, the development of real 3D breaklines is still a problem, and Bolch and Schröder (2001) actually concluded that the integration of simple breaklines does not significantly improve the overall quality of the DEM. As a solution, in their DEM generation process Kamp et al. (2005) manually added some contour lines using elevation information from stereoscopic analysis of aerial photographs. Eventually, the TIN DEM was converted into a grid-based DEM using Esri ArcInfo 7.2 software, and two nearest neighbor filters helped smooth the final model, albeit at the expense of some topographic detail (e.g., the loss of some edges, frost cliffs, and gorges). The authors concluded that the final DEM was of sufficient quality for macro and mesoscale geomorphological analysis (e.g., of rock glaciers); however, processing the DEM from contour lines was relatively time consuming.

5.3.6 Data fusion

While small gaps in DEM data can be filled by interpolation, large voids stemming from shadowing, correlation failures, and other effects require a different approach. It is sometimes desirable to combine, or fuse, DEMs from different sources in order to obtain the most complete coverage of an area. As well as filling in any gaps in the respective DEMs, such fusion can also help to identify any severe vertical and horizontal errors in common areas (Kääb et al. 2005). DEM-merging techniques range from replacement of data (Kääb 2005a) and weighted fusion, resulting in smooth transitions between DEMs (Weidmann 2004), to merging in support of DEM processing itself (e.g., DEM approximation in order to geometrically constrain stereo parallax matching or interferometric phase unwrapping) (Honikel 2002). One successful approach involves identification of artifacts in a single-scene ASTER DEM and then infilling with a global dataset such as SRTM or the ASTER GDEM. Artifact delineation is almost perfect (almost no errors of omission or commission), so the infilled product is usually of very high quality (Crippen 2010).

The ASTER G-DEM1 is the result of the fusion of suitable individual ASTER-derived DEMs by averaging all elevations in the vertical stack. While DEM fusion using this approach is helpful for deriving a spatially more complete and accurate set of geomorphometric parameters, it should be avoided or handled with care for DEM-based studies of glacier thickness changes. The number of stereo images used to produce a given G-DEM1 grid point elevation varies from one to several tens. Whereas the number of scenes used for each grid point is known globally, G-DEM1 ancillary data do not support knowledge of when the images were acquired. The mean date is about 2004/2005, but for a given locale it could be earlier or later by a few years. Variance of the mean from 2004/2005 is less than a year in most areas, but it can be much greater for some places where few ASTER images have been acquired. G-DEM1 carries some of the artifacts present in individual DEMs, and is generally very noisy, often rendering it unsuitable for detailed studies requiring high resolution, although for studies of basin-scale hypsometry, G-DEM1 can be convenient. A new G-DEM2, of similar construction but lacking the severity of noise and artifacts of the earlier version, was released in October 2011. G-DEM2 benefits from 260,000 additional ASTER scenes, and preliminary tests indicate improved accuracy in both horizontal and vertical dimensions, and a substantial reduction in the number of voids (Tachikawa et al. 2011). Still remaining for the future is development of a new GDEM that would allow better tracking of input images.
5.4 DEM ERROR AND UNCERTAINTY

5.4.1 Representation of DEM error and uncertainty

Given the number of stages involved in generating a DEM, errors are inevitable in both the vertical and planimetric coordinates. In general, error can be classified as: (1) gross errors that are associated with equipment failure; (2) systematic error that represents the results of a deterministic system that can be accounted for by using functional relationships; and (3) random errors that occur within (or because of) the multitude of operational tasks that are involved in computation. In this context, error is typically defined as systematic and/or random variations about a “true” reference value (Fisher and Tate 2006). The magnitude of vertical error can be an important consideration, as changes in glacier surface altitude over shorter time frames may become undetectable, depending upon the nature of the source data. Consequently, the usefulness of a DEM for estimating mass balance must be carefully evaluated (Bamber and Payne 2004).

A common descriptor of error is root mean square error (RMSE):

$$RMSE = \sqrt{\frac{\sum_i \sum_j (z_{i,j} - z_{i,j,r})^2}{n}}$$

(5.1)

where \(z_{i,j}\) is the elevation at location \((i,j)\) in the DEM, and \(z_{i,j,r}\) is a reference elevation at the same location. The metric has been used when comparing elevations off-glacier in a variety of glaciological studies, although it does not describe very well the statistical distribution of vertical error (Fisher and Tate 2006). It has, however, become a standard measure of map accuracy. Other researchers have used additional error metrics such as mean error \((ME)\) and standard deviation \((S)\) (Cuartero et al. 2004):

$$ME = \frac{\sum_i \sum_j (z_{i,j} - z_{i,j,r})}{n}$$

(5.2)

$$S = \sqrt{\frac{\sum_i \sum_j [(z_{i,j} - z_{i,j,r}) - ME]^2}{n - 1}}$$

(5.3)

Systematic under or overestimation (biases) are depicted as positive or negative ME values.

Such global summary (single-value) metrics are quick to calculate and easy to report, but they fail to characterize the spatial pattern of error, which is critical to environmental applications. DEM errors can vary spatially, and research indicates that the spatial structure of error in DEMs remains poorly understood (Carlisle 2005). Numerous researchers have attempted to study and describe the nature of spatial error and have found that patterns of error can be anisotropic, scale dependent, spatially variable, and spatially correlated, but most importantly DEM error is closely related to the complexity and characteristics of the terrain (Kyriakidis et al. 1999). Work in alpine environments often reveals patterns of error over mountain terrain and glacier surfaces that are highly variable in spatial extent and location, and are related to acquisition of source data, spatial interpolation, and terrain geometry.

5.4.2 Type and origin of errors

Once a DEM has been generated by determining the parallax between pixels matched by cross-correlation there is always a need for postprocessing due to mistakes in pixel matching, correlation failures, and, if present, the impact of clouds in the scenes. Further, shadowing in regions of high relief, low image contrast over clean snow and ice, and self-similar surface features on glaciers will lead to voids and artifacts in the resulting DEM. Some software packages, such as SilcAst, will try to remove such features automatically, with no user control over the process. Alternatively, ENVI, LPS, and PCI Orthoengine all provide a suite of postprocessing tools for manual editing. However, Eckert et al. (2005) found that in some cases the postprocessing tools provided by software packages were not sufficient and further morphologically based interpolation algorithms were required to produce a suitable DEM. Such matching mistakes and voids are relatively easy to identify and correct for, but where inaccurate GCPs and poorly chosen tie points are used, distortions, biases, and planimetric shifts may also be introduced into the derived DEM, which can be difficult to model without the use of a reference elevation dataset. This is particularly problematic where multitemporal DEMs are required for the measurement of elevation changes (see Section 5.5.5).

Two types of error affect the measurement of glacier elevation changes: horizontal (planimetric) and elevation (altimetric). Planimetric error refers to horizontal shift of often correct elevation values to erroneous easting/northing locations. This can be either a systematic or a variable shift, and can be exhibited in one or more directions. Such shifts are easily quantified by correlating corresponding orthoimages and quantifying the orthophoto paral-
lax (Li et al. 1996, Georgopoulos and Skarlatos 2003), since there should be no relief displacement in either image if the DEMs are accurate. Altimetric error refers to systematic biases that may artificially increase or decrease elevation in a given direction across part of, or the whole, DEM, as well as more locally variable slope or aspect-related biases (Fig. 5.4). The correction of both types of error usually requires some form of mathematical modeling. The most promising approach has focused on the use of ordinary least-squares regression modeling to create spatially nonstationary, spatially correlated and heteroskedastic error surfaces from only a small number of sample locations (Kyriakidis et al. 1999, Carlisle 2005). These error surfaces can then be used either to create higher accuracy DEMs, or to inform analyses of error propagation in the computation of surface derivatives (Oksanen and Sarjakoski 2005). It is crucial that both planimetric and altimetric errors are identified, particularly in the case of glacier monitoring as they can lead to erroneous volume changes (Schiefer et al. 2007) or even change the sign of the resulting mass balance calculation (Berthier et al. 2006).

Systematic errors are common in some of the most widely available topographic datasets, making it essential for users to make appropriate error assessments, even if they believe biases are removed prior to analysis. Particularly relevant in this respect is the widely used continuous DEM produced by the Shuttle Radar Topography Mission, which was flown in February 2000 and provides a topography covering continental areas from 60°N to 56°S (Rabus et al. 2003) with a 1 and 3 arcsec spatial resolution (about 30 and 90 m, respectively). It has yielded significant advances in the monitoring of glacier wastage in Alaska and neighboring Canada (Muskett et al. 2003, Larsen et al. 2007, Schiefer et al. 2007, Berthier et al. 2010), Patagonia (Rignot et al. 2003, Rivera et al. 2005), and central Asia (Surazakov and Aizen 2006). However, since its release, significant biases in SRTM data have been identified by a number of authors, and a clear examination of the bias still needs to be performed. For example, Kääb (2005a) found a systematic mean error of about 7 m for the Gruben area in Switzerland. Still in the Alps, Berthier et al. (2006) found a small mean error (<3 m) but detected a bias that increased linearly with elevation. Such a bias related to elevation is still not fully understood but has since been confirmed for Patagonia (Möller et al. 2007), the Himalayas (Berthier et al. 2007), and the Canadian province of British Columbia (Schiefer et al. 2007). The latter authors used a piecewise model to correct elevation bias (constant bias at low elevation and linear bias above a threshold altitude). The regional pattern of the biases in SRTM data is also complex. Surazakov and Aizen (2006) found a localized ice-free region with systematic error in the SRTM data ranging from −20 to 12 m on a 30 km spatial scale. Berthier and Toutin (2008) found a 20 × 20 km region where SRTM data are systematically 5–10 m higher than SPOT5 or ICESat elevation data. Note here that, although sensor platform orbits are too widely spaced for mountain glacier elevation change mapping, ICESat elevation profiles have been shown to be a good source of data to detect and understand errors in SRTM data for ice-free regions where no elevation changes are expected (Carabajal and Harding 2005, Berthier and Toutin 2008).

5.5 GEOMORPHOMETRY

Glacier geomorphometry refers to the three-dimensional topographic characteristics of a glacier surface including its size, shape, hypsometry, orientation, and position. Geomorphometric analyses have historically pursued fine-resolution digital elevation models to improve and refine land

![Figure 5.4. Scatterplot of mean difference altitude generated from a SRTM DEM (2000) and an ASTER-derived DEM (2004). Mean values were computed off-glacier over the Nanga Parbat Massif in Pakistan. Variations in viewing geometry and/or spacecraft orbital parameters result in a nonlinear bias that significantly deviates from zero. Consequently, linear and nonlinear systematic biases must be removed when comparing DEMs generated from different sensor products.](image-url)
surface parameters and objects (Drăguţ et al. 2009). However, with the increasing availability of detailed DEMs it is becoming clear that the relationship between DEM scale and the ability to extract geomorphometric information is not straightforward. Indeed, for many applications, increased DEM resolution only serves to introduce noise into the analysis. Accordingly, a number of methods have been applied to account for scale-related problems through DEM generalization, although further work along these lines is needed if accurate topographic characterization of glacierized areas is to be achieved (Drăguţ et al. 2009). Despite this current imperfection, many quantitative analyses of landscape and landscape evolution remain heavily dependent on the derivation of geomorphometric data in their methods.

5.5.1 Geomorphometric land surface parameters

When deriving geomorphometric information from DEM data it should be noted that, for every order of differentiation, the effective resolution of the product declines and noise increases. The first derivative (based on calculations between two points) normally defines slope, whereas the second derivative (based on calculations between three points) normally defines curvature. For every order of differentiation, small errors in the primary data-set become exaggerated. Thus, a DEM having a 30 m posting can report the first and second derivative values still with 30 m postings, but each grid cell of the derivatives includes information from neighboring cells and so the effective resolution is reduced for the derivatives, even though a value is computed for each grid cell. Effectively this means that derivative information for very small glaciers is useless, especially if the derivatives, such as curvature, are used to define lateral moraines, computed drainages, or other landforms or hydrological units. Thus, differential geomorphometric parameters carry both great power to discriminate distinct terrains and landforms, and great risk that noise or systematic bias is transmitted into geomorphometric mapping products.

Depending on the tolerance for noise or low spatial resolution, geomorphometric analysis can emphasize nondifferential parameters (based on hypsometry), first-order differential analysis (slope, slope aspect), or second-order differentials (curvature, tangential curvature) (Fig. 5.5). Most off-the-shelf image-processing software is capable of producing such metrics using standard algorithms, with the quality of the derived geomorphometric data being largely dependent on the accuracy of the input elevation data. In an applied context, land surface parameters are a useful means of comparing the topographic characteristics of glacierized areas and, in addition, are increasingly being used in combination with satellite imagery to derive more robust approaches to accurate glacier delineation (see Chapter 4, and Section 5.6 for further details). They are also often employed in process modeling, with elevation providing useful information on gravity-driven processes. For example, land surface parameters such as slope gradient can indicate the gravitational potential available for geomorphic work (i.e., erosion), and slope aspect the direction of the work carried out (Smith and Pain 2009).

It is important to note that geomorphometric data may vary dramatically between adjacent sub-catchments and, less obviously, for the same glacier or glacierized area through time. Changes in glacier topography, for example, may be caused by a sustained change in mass balance, or by a change in ice dynamics (or both). Basic elevation data reflecting these changes may be derived by taking a topographic profile along the flow line of the glacier from multitemporal DEMs or by computing the altitude–distance function, which effectively compares every pixel representing the surface of the glacier to a terminus position by plotting the average altitude in a distance bin. More complex elevation change data can be derived by hypsometric analysis, essentially a frequency analysis, characterizing the altitude–area distribution of a glacier surface. However, the generation of more complex data such as these is not always desirable; for example, small changes in surface elevation may be easily detected in simple multitemporal topographic profiles, but not so in a multitemporal hypsometric analysis where large volumes of (potentially noisy) data can mask subtle surface changes. Whichever geomorphometric approach is adopted, it is essential that systematic biases in the DEM are removed prior to analysis and interpretation of the results (see Section 5.4).

5.5.2 Scale-dependent analysis

A range of interacting geomorphic processes shape the glacial environment, leading to landforms that are rarely strictly spatially delimited (Schneevoigt and Schrott 2006). Such landforms are diverse in size and shape, even within a single land cover...
classification, and microscale landforms may compose local-scale landforms, which may themselves compose catchment-scale landforms. In modeling such dynamic and diverse environments, linear process-form relations and those that are spatially restrictive are therefore unrepresentative. There is thus increasing focus on the hierarchical organization of topography in studies on mountain geomorphology, and the subsequent adoption of scale-dependent analyses. These can be simply defined as methods that examine the variability of the three-dimensional spatial structure of morphological features on multiple levels.

With the increasing availability of DEMs from airborne and spaceborne platforms, automated approaches have been developed to identify specific geomorphometric features (e.g., glacier extent, location and density of crevasses) based on their shape and textural properties. One such method is to measure surface roughness on multiple scales and in multiple directions, by variogram analysis. The variogram is effectively an index of dissimilarity between pairs of points that are separated by a predefined vector and within a specified search window. Multiple variograms can be used to characterize terrain morphological features, such as debris flow deposits, channels, and rockfall deposits, and to calibrate secondary morphological indices such as anisotropy, periodicity, and the spatial variability calculated at specific lags. These indices, while providing useful quantitative landscape characterization data in their own right, can then

Figure 5.5. Geomorphometric analysis of the Batura Glacier, Hunza Valley, Pakistan: (a) SPOT HRVIR panchromatic satellite imagery (acquired October 17, 2008), copyright CNES 2008/Distribution Spot Image. (b) SPOT HRS-derived composite DEM (image dates 2002–2004), from which (c) slope, (d) aspect, (e) shaded relief, and (f) plan convexity, can all be calculated. Figure can also be viewed as Online Supplement 5.1.
be used as input into further, perhaps more complex (e.g., pattern recognition) landscape classification techniques (van Asselen and Seijmonsbergen 2006).

A further derivative of the variogram is the fractal dimension ($D$), which provides a measure of whether topographic surfaces and spectral reflectances of land cover units are self-similar over a range of spatial scales. Many landscape features and other environmental data have been shown to exhibit self-similarity, at least statistically (Goodchild and Mark 1987). The limited number of studies that have evaluated the utility of fractals for these purposes indicate that the majority of geomorphic surfaces exhibit scale-dependent fractal dimensions (i.e., limited to certain spatial ranges; Bishop et al. 1998), with the range in scales often determined by the controlling geophysical processes that have shaped, or continue to shape, the landscape (Lathrop and Peterson 1992). Fractal dimensions have also been employed to improve classification accuracy (de Jong and Burrough, 1995) and to provide insight into operational-scale and process–structure relationships. This approach appears to have great potential in this respect, although to investigate self-similarity in surface roughness characteristics over the full range of spatial scales requires the use of high-quality DEMs, which may not always be available in glacierized areas.

5.5.3 Topographic radiation modeling

Digital elevation models are fundamental to the three-dimensional modeling of solar radiation variation across a landscape. Insolation modeling can either be point specific or area based. Point-specific modeling considers the geometry of surface orientation, the visible sky, and the effect of local topography. Local topographical effects can be determined using empirical relations, visual estimations, or, where field data are logistically possible, by upward-looking hemispherical photography. Such calculations can give locally very accurate results, but are clearly limited in spatial coverage. Area-based insolation modeling relies solely on the use of a DEM to calculate surface orientation and shadowing across a subcatchment, for example, and as a result has much greater application for understanding large-scale landscape processes. Along these lines, a number of studies have made surface irradiance and ablation gradient calculations to identify locations most suitable for past and present glaciation (Carr and Coleman 2007, Allen 1998) by identifying site shelter and exposure, and to be applied as input to energy balance melt models, which are clearly fundamental to understanding the relationship between glacier behavior and climate.

Net radiation (also known as net flux) is defined as the balance between incoming and outgoing energy and can be computed as:

$$Q_n = E(1 - \alpha) + L_\uparrow + L_\downarrow + L_t$$

where $E$ is total surface irradiance, $\alpha$ is surface albedo, $L_\uparrow$ is longwave sky radiation, $L_\downarrow$ is longwave radiation from the surrounding terrain, and $L_t$ is emitted longwave radiation. It is regulated by numerous processes and can be highly variable depending on atmospheric, topographic, and surface biophysical conditions. Indeed, in mountainous areas radiative fluxes are particularly complex, fluctuating considerably in space and time because of the effects of slope, aspect and the effective horizon, and the input of reflected and emitted radiation from surrounding slopes (Hock 2005). As such, there is a movement towards the use of increasingly fine temporal (hourly) and spatial (~25 m) resolution modeling, with the latter again dependent on the availability of suitably fine-resolution and accurate digital elevation data. Where such data do exist, studies have shown that the melt rate of snow and ice and spatial and temporal patterns in energy balance can be calculated accurately across a glacier, albeit with dependence on accurate field and meteorological data (Brock et al. 2000).

5.5.4 Altitude functions

Most glacier parameters vary as a function of altitude, and these relationships can give insight into glacier dynamics and processes that simple two-dimensional analyses would not reveal. A glacier’s most fundamental altitude parameter is the equilibrium line altitude (ELA) because it divides the glacier into accumulation and ablation areas (Braithwaite and Raper 2010). This can be simply estimated using multispectral satellite imagery in combination with a DEM, by assuming that the ELA is equal to the snow line position at the end of the melting season (Bamber and Rivera 2007). Such information is fundamental to mass balance calculations, which are useful indicators of climatic variations where no actual ELA data or better alternative proxies exist (Yadav et al. 2004). In the absence of calculated mass balance data or transient end-of-season snow line data,
the topographic profile of a glacier can be used as a relative proxy for the dynamic state of glaciers, with those glaciers in rapid recession tending to exhibit concave-up or flattened (planar) surface profiles in the ablation zone, and those accumulating or maintaining mass characterized by convex-up surface profiles (transverse profiles especially) in the ablation zone (Quincey et al. 2009).

The altitude–area profile (or the hypsometric curve) for each glacier represents a distinct 3D spatial signature that is the end result of thousands or millions of years of erosion and reflects interaction of the regional climate with subglacial bedrock (Tangborn 1999). It has been used in many cases to infer the state of geomorphic development within a glacial system (Katsube and Oguchi 1999). Glacier erosion processes are determined most significantly by glacier velocity, ice thickness, subsurface geology, and basal thermal conditions. Differential erosion therefore occurs with altitude as each of these parameters changes accordingly. Topographic analyses of the Nanga Parbat Massif in Pakistan revealed a spatially variable relief structure that correlated to geomorphic events and dominant surface processes (Bishop et al. 2001). Glaciation was found to generate the greatest mesoscale relief at high altitudes and warm-based glaciation was found to reduce relief at intermediate altitudes. More recently, numerical modeling has shown that mountain heights can be explained by a combination of glacier erosion above the snow line and isostatic uplift caused by erosional unloading, with maximum elevations being constrained to an altitude window just above the snow line (Egholm et al. 2009).

More generally, glacier hypsometry determines how responsive glacier-wide mass balance is to climatic perturbations (Furbish and Andrews 1984). For example, a rise in the snow line of 200 m in a given region (in response to local atmospheric warming, for example) would have a much greater impact on a low-gradient valley glacier than a steeply sloping one, as in the former case a greater proportion of the overall ice mass would become subject to net annual mass loss. Thus, as an example, if there were a rise in local atmospheric temperature in the Hunza Valley of the Karakoram, the mass balance of the Batura Glacier would be affected to a greater extent than that of the Ghulkin Glacier, and the mass balances of the Pasu and Ghulmit Glaciers would change somewhere between those two end members (Fig. 5.6). Similarly, glacier clinometry (characterization of the slope/altitude function) expresses glacier relief, and is thus also useful for determining erosion rates and mass balance fluctuations.

The relationship between altitude and glacier velocity is not straightforward. Glaciers with low relief tend to exhibit flow that is relatively uniform across the altitudinal range, whereas those with high relief (and are thus fed predominantly by snow and avalanche material) tend to have very high flow rates at altitude and much reduced flow towards their termini. Altitude–velocity profiles can be useful for proxy assessments of mass balance (Luckman et al. 2007), for identifying areas susceptible to glacial lake development (Quincey et al. 2007), and for determining predominant glacier flow regimes (Copland et al. 2009). In the case of the latter, generally flat transverse velocity profiles with a rapid reduction in flow at the margins indicate “block flow”, suggesting down-glacier movement of ice en masse by basal sliding, whereas convex velocity profiles that display greatest displacements towards the centerline of the glacier indicate a flow regime dominated by ice deformation. Large seasonal variability in flow can further highlight the importance of meltwater availability for a given glacier, and may even help to identify different flow mechanisms that exist at different altitudes within a single glacial system (Fig. 5.7; Quincey et al. 2009).

5.5.5 Glacier elevation changes and mass balance calculations

Stereo photogrammetry has been employed to calculate glacier surface elevation changes for many
years, using images acquired by both airborne and satellite sensors. The most reliable source of DEMs for volume change estimates is still aerial photos. Given their very fine resolution, if precise GCPs are available, DEMs with RMS accuracies the size of approximately one pixel (few tens of centimeters) can be obtained (Kääb 2002). Consequently, aerial DEMs are still frequently employed to study volume changes at the scale of a single glacier and detect systematic errors in cumulative mass balance estimates obtained from the traditional (pit and stake) glaciological method (Østrem and Haakensen 1999). However, aerial photographs cover a limited surface on the ground (generally one glacier) and it is difficult to fly a plane in remote and high-relief areas. Consequently, they cannot be regarded as a means of obtaining regular coverage of glacier topography at the regional scale. Given the large footprint of satellite images (typically $60 \times 60$ km), it is tempting to apply the geodetic method to spaceborne DEMs. The principle is the same as for aerial photography: two sequential glacier surface models are derived from pairs of stereoscopic images and subtracted to yield a map of elevation changes. Satellite-derived DEMs are less accurate than those computed from aerial photographs so caution must be taken when interpreting the signal and comprehensive error analysis is mandatory.

Changes in surface elevation can be measured most accurately by processing all imagery within a single block or, put more simply, using a single mathematical model (Kääb 2000; Fig. 5.2). The quality of derived surface elevation data using this technique is mainly dependent on the interior orientation of the stereo model (Baltsavias 1999) rather than the accuracy of any ground control used, which makes the technique particularly appropriate for assessing remote terrain. Factors such as scanned resolution of the images, accuracy of fiducial mark locations, and accuracy of camera calibration parameters are particularly important in such analyses. Model GCPs introduce a second-order error that is small (of the order of a few percent) in relation to final vertical displacements, which is consistent between the two DEMs, providing they are bundle-adjusted as a single image block. Therefore, the technique can, in theory, be used without any ground control at all, while still

Figure 5.7. Selected seasonal and annual centerline velocity profiles for the Baltoro Glacier, Pakistan Karakoram. Date format is year, month, day. Note varying flow rates across summer and winter seasons, and varying patterns with altitude. In particular, note the similarity of flow profiles in the lowermost 400 m of the glacier, and contrasting profiles with greater altitude, which may be related to the availability of meltwater at the glacier bed.
producing accurate vertical displacement results from the relative image orientation alone (Kääb 2002).

A major source of error in vertical differences between multitemporal DEMs is their three-dimensional co-registration. In cases where no common GCPs and tie points have been applied, severe biases might exist in particular between space-derived DEMs. Errors in elevation differences from such a lack of precise co-registration might easily exceed real elevation changes, and should therefore be investigated as part of every DEM-differencing work (cf. Fig. 5.4). The most efficient method to investigate and possibly correct DEM biases is the cosine method that relates elevation differences found for stable terrain to the combination of terrain slope and aspect (Kääb 2005a, Nuth and Kääb 2011).

While a 10–20 m elevation error may be acceptable for the orthorectification of images, it is not for glacier elevation change mapping. Typically, a glaciologist aims at measuring the rate of change in surface elevation within ±0.5 m/yr (this is the upper bound for the error). Larger errors are acceptable only when massive (tens of meters), but unusual elevation changes are monitored (Stearns and Hamilton 2007). A glaciologically relevant accuracy can be obtained by (1) increasing the time period between the two datasets and/or (2) improving the quality and limiting the biases of the DEMs. The first strategy is generally explored by comparing recent spaceborne DEMs (ASTER, SRTM, SPOT) with maps from the 1950s, 1960s, or 1970s. Applying such historic topographic datasets with more recently derived DEMs may permit determination of glacier elevation changes across several time-steps. For example, Kargel et al. in this book’s Figure 15.4F show a technique that captures three sequential DEM elevation-differencing analyses (over a 40-year total period) into one RGB composite image. Each color channel (RGB) represents the earliest, middle, and the latest elevation-differencing analysis, respectively; the compositéd image provides immediate visual perception of the acceleration or deceleration of elevation changes coincident with the color-scaled time period. In this way, spatial, dynamic, and multitemporal information on elevation changes are uniquely viewed within one image. The second strategy relies on higher resolution satellite images with stereo capabilities such as SPOT5 HRS or ALOS PRISM. Even in the latter case a minimal image time span of about 3 to 5 years is required.

The accumulation zone is the most critical part of the glacier when mapping elevation changes. If DEMs are derived from optical images or aerial photographs, the high reflectance of the year-round snow-covered accumulation zone may lead to limited features in the photographs/images or, in the worst case, saturation of the sensor (Kääb 2002). In the case of old maps derived from aerial photographs, errors may have been introduced by interpolation of contours (Schiefer et al. 2007). For satellite images, featureless terrain can lead to data gaps or erroneous pits and spikes in DEMs of the accumulation zone. Enhanced elevation change errors may also affect the accumulation zone because the ice-free regions, which are used for detecting and modelling any elevation biases, are located at lower altitude. Only a few nunataks may be visible to check the presence of relative elevation biases at higher altitude, but, in practice, even this is difficult because they are generally steep and small features. Consequently, any elevation biases need to be extrapolated from the lowest to the highest elevations. Other reasons for increased uncertainties in the accumulation zone relate to difficulty in choosing density values to convert volume-to-mass changes and, when DEMs derived from SAR images are used, the necessity to take into account penetration of the radar signal (depending on its frequency) into the snow/firn (Rignot et al. 2001). Consequently, good practice is to compute separate estimates of glacier volume changes for the ablation and accumulation zones, even if only a rough estimate of the position of the equilibrium line altitude (ELA) is available. Different uncertainties can thus be attributed to each of the two regions.

A number of strategies exist to actually compute glacier volume changes from a set of glacier elevation changes (Kääb 2008). (1) If the two (or more) DEMs to be differenced are complete, the summation of vertical differences gives the volume difference. Since this is often not the case (see above), either (2) the hypsographic method can be used where mean thickness change for each elevation bin is multiplied by its area and all bins summed, or (3) polynomial variation of elevation changes with height can be fitted to measured elevation differences and the elevation differences for each glacier point then computed according to its height using the polynomial parameters. In cases where one of the multitemporal elevation datasets is not a grid, or elevation information is distributed unevenly, such as in contour lines or altimetry
footprints, calculations must be made carefully. For example, it might be advantageous in terms of minimizing error propagation not to interpolate point elevation data to a DEM and then difference two datasets, but rather to first calculate differences between the elevation points and the DEM, and then to interpolate elevation differences across the wider glacier surface. In a number of cases, elevation differences will show less spatial variability than elevation itself, and interpolation routines will thus produce less serious artifacts.

Data from nonoptical sensors can also provide accurate measurement of glacier surface elevations and, with multitemporal datasets, elevation changes. Spaceborne radar altimeters (on board ERS-1, ERS-2, or Envisat, for example) are well suited to flat and large ice sheets or ice caps but are not suitable to survey mountain glaciers targeted by GLIMS because of their kilometric footprints. The smaller (60 m) footprint of the Geoscience Laser Altimeter System (GLAS) on board ICESat makes it a potential source of data for large mountain glaciers and ice caps (Zwally et al. 2002). However, the large spacing of the orbits, the fact that they are not repetitive, and the difficulty of removing the influence of clouds limit the usefulness of ICESat data. Still, ICESat data can be used to evaluate the quality of other DEMs (Berthier and Toutin 2008) or to estimate glacier elevation changes when compared with other multitemporal elevation data (Sauber et al. 2005, Surazakov and Aizen 2006, Kääb 2008). Repetitive surveys by airborne laser altimetry have been shown to be extremely accurate. However, central line surface profiling may lead to errors due to the difficulty of extrapolating to the whole glacier surface (Arendt et al. 2006).

It is clear then that DEMs derived from remote sensing can provide glacier elevation change data on a range of temporal and spatial scales. While useful in their own right, elevation change data are also a fundamental component of glacier mass balance calculations. If two DEMs cover the whole glacier, their difference (i.e., volume change) can be converted to mass balance assuming a constant density of 900 kg m$^{-3}$ in the ablation area, although the true density value to use in the accumulation zone is still the topic of ongoing research. Most authors use the same density as in the ablation zone, as using a density different from 900 kg m$^{-3}$ implies a change in the rate of densification. Ideally the calculation should include quantification describing any shift in the underlying ground (e.g., due to isostatic rebound or tectonic movement) although in reality this is normally small compared with glacier surface elevation change. The ultimate result is mass balance quantification expressed in meters water equivalent (MWE) over the imaged time period.

A number of studies have used this approach to assess the mass balance of alpine glaciers, using combinations of historical topographic maps (Rivera et al. 2007) and DEMs derived from SPOT imagery (Berthier et al. 2007), SRTM (Racoviteanu et al. 2007), ASTER (Khalsa et al. 2004), Corona (Bolch et al. 2008), and laser altimetry (Sauber et al. 2005). Very few have compared remotely sensed mass balance calculations with those derived by field investigation, but those that have (e.g., Hagg et al. 2004, Rabatel et al. 2005, Zemp et al. 2010) have found good agreement between dataset results. As noted above, because of the limited accuracy of elevation data derived by remote-sensing methods, many studies have strived to obtain mass balance estimates derived over longer, preferentially decadal time-scales, to ensure the change in observed data exceeds the uncertainty in the approach.

### 5.6 Glacier Mapping

Snow and ice exhibit distinct spectral properties that make accurate delineation of debris-free glaciers possible using a variety of remote-sensing techniques (e.g., thresholded ratio images), but the automatic classification of debris-covered ice is more complex, because of the inherent difficulty of spectrally distinguishing supraglacial sediment and landslide material from that present in the surrounding terrain (Paul et al. 2004b). For this reason, DEMs are widely used for terrain visualizations and to provide additional information on landscape morphometry, land surface context, and spatial topology, all of which facilitate a more accurate and reliable classification result for debris-covered glaciers.

At the most basic level, DEM data can be used to generate terrain visualizations to aid the manual delineation of glacier boundaries (Fig. 5.8). Glacier termini are often difficult to identify using planimetric imagery alone because, particularly when heavily debris-covered, they appear contiguous with the proglacial zone, but small elevation variations visible in three-dimensional visualizations can
sometimes remove this ambiguity. Similarly, the exact location of a catchment divide may be unclear, especially where fresh snowfall masks the headwall ridge; three-dimensional information is particularly useful in this respect. For the glacier itself, DEM data are useful for identifying areas of low slope angle (see Fig. 5.5b), which are characteristic of debris-covered glacier tongues in most parts of the world. When combined with complementary data such as land cover classifications, and with results from neighborhood and change detection analyses, it has been shown that slope angle data can be used as the primary morphological characteristic to delineate glacierized terrain (Paul et al. 2004b, Bolch et al. 2007). However, specific slope thresholds used to delineate glacier facies vary from region to region, with ice masses in the European Alps generally characterized by short, steep tongues relative to the long (>10 km) flat tongues of parts of the Himalaya, for example. Further, this approach depends on slope angle being calculated across a sufficiently broad spatial kernel to avoid highlighting local slope variability (e.g., natural peaks and troughs across the glacier surface), while retaining sufficient detail so that small-scale features such as inner moraine flanks are not excluded from the analysis.

Additional first-order information that can be calculated from DEM data include landscape plan and profile curvatures, which can be used to define both glacial and nonglacial landform elements (Bolch and Kamp 2006; see Fig. 5.5c–f). By clustering surfaces with similar curvature characteristics it is possible to differentiate between glacier surfaces and valley bottoms (low convexity), ridges and lateral moraines (high convexity), medial moraines (moderate convexity), and transitions between glacier margins and lateral moraines (high concavity). A similar but more complex approach is to use hierarchical object-oriented modeling, which employs various DEM-derived terrain object properties such as slope angle, slope azimuth, curvature, and relief to identify locally contiguous portions of the landscape, which are iteratively aggregated to form higher order landform objects at smaller and smaller scales (Bishop et al. 2001). Glacier boundaries can thus be delineated at a landform level, and objects and the relationships between objects can be used for further landscape analyses, such as studying the role of surface processes (e.g., erosion/uplift) in topographic evolution. Morphometric approaches such as these show great potential for glacier mapping across the world, but are heavily dependent on the input of high-quality DEM data for accurate results.

A range of satellite sensors already have stereoscopic imaging capability and some recent missions (e.g., Cartosat-1, ALOS PRISM, Terra-SAR-X, and the TanDEM-X-mission) have significantly increased the potential for extracting DEM data at very high resolution for use in glacier mapping. For many remote high-mountain regions of the world, however, gaining access to high-quality DEMs can be problematic, with ASTER and SRTM data often providing the best (or only) available sources. Errors common in ASTER-derived DEMs of steep, high-mountain relief can sometimes
produce artifacts in classification results, but may still provide a quality of output that exceeds classification methods not employing a DEM of any sort (Paul et al. 2004b). DEM resolution can be an equally important consideration, with aerial photography DEMs (such as those provided by the Swiss Topo Survey) outperforming satellite sensor–derived data in almost all cases (Bolch and Kamp, 2006), particularly in the delineation of small ice masses. In areas where accurate and fine-resolution DEMs are not available, manual digitization of small samples may still therefore be necessary to achieve a satisfactory classification result. Therefore, attempts have been made to introduce additional information into the classification process, such as metrics relating to geomorphometry, texture, and context (Bishop and Shroder 2000, Bishop et al. 2001, Taschner and Ranzi 2002, Paul et al. 2004b, Ranzi et al. 2004, Buchroithner and Bolch 2007, Bolch et al. 2008). Sophisticated classification approaches use both first and second-order topographic derivatives to segment landscape units accordingly, and make use of statistical, artificial intelligence and hierarchical–structural methods.

5.6.1 Pattern recognition

Pattern recognition techniques perform two key tasks: description and classification. Given an object (or set of objects—pixels in a satellite image, for example), pattern recognition systems first seek to describe those object(s), often in three dimensions, and subsequently classify the objects based on those descriptions. The rigor with which the prior task is performed largely governs the quality of the latter. The description and classification of input data in this way can be handled by statistical or structural methods or, more frequently, a combination of both (the hybrid approach). Statistical methods make use of decision theory concepts to segment the landscape based on their quantitative features, whereas structural methods make use of syntactic grammars to segment the landscape based on the arrangement of their morphological features (see Section 5.6.3). Either way, DEM data are a fundamental input to the classification procedure.

Statistical pattern recognition techniques are largely dependent on the choice of model parameters, the quality of the expert knowledge used in the prior part of the model, and the resolution of the image and DEM data. For example, and with specific reference to debris-covered glacier classification, let $R$ denote the pixel domain of a set of co-registered data layers (e.g., satellite imagery, elevation and geomorphometric parameters). Combining all these layers into vector space results in a feature vector per pixel. Similar vectors can be derived to describe a shading field (to handle across-image slope and exposition variability) and a segmentation field, such that:

- $\tilde{x} : R \rightarrow \mathbb{R}^m$ vector field of features (observable)
- $\tilde{\alpha} : R \rightarrow \mathbb{R}^m$ shading field (unknown)
- $s : R \rightarrow K$ segmentation field (unknown)

where $K$ denotes the set of labels used for segmentation. In the simplest case there are only two possible labels—one for a debris-covered glacier and another for “background”, but more are usually employed to gain a full description of the environment. The statistical model relates the three quantities (above) by a probability distribution:

$$p(\tilde{x}, \tilde{\alpha}, s) = p(\tilde{x} | \tilde{\alpha}, s)p(\tilde{\alpha})p(s)$$

where it is assumed that shading and segmentation are $a$ priori independent.

If the parameters of the normal distribution are already known, then the recognition task simply requires the following: given the observation field $\tilde{x}$ we have to estimate the best shading field $\tilde{\alpha}$ and then estimate the best segmentation field $s$. Routine algorithms such as the Gibbs sampler (Geman et al. 1990) and the Expectation Maximization algorithm (Schlesinger 1968, Dempster et al. 1977) are normally employed to make the estimations.

If the parameters of multivariate normal distributions are unknown (first factor in the equation above) they can be estimated by maximum likelihood learning given an expert’s segmentation of the scene. In this case the Expectation Maximization algorithm is again applied but with partial supervision. The expert’s segmentation is relaxed by defining only three regions: background, foreground, and a zone between, leaving the system to learn the optimal boundary. The resulting iterative learning scheme comprises repetition of the following subtasks:

1. Given the actual parameters of the normal distributions and the actual estimation of the shading field, sample the segmentations and estimate the marginal probabilities $p_r(s_r = k | \tilde{\alpha}, \tilde{x})$ for each pixel $r$. 
2. Use these marginals to improve the parameters of the normal distributions (i.e., the covariance matrices and mean vectors for all segments).

3. Re-estimate the shading field based on the current marginal probabilities and parameters of the normal distributions.

When the optimal boundary is reached, the iteration is stopped and the pixels are assigned their segment label (Fig. 5.9).

5.6.2 Artificial intelligence techniques

Artificial intelligence techniques (often referred to as knowledge-based systems) essentially comprise a set of logical rules that provide an analog for the reasoning used in anthropogenic decision making. These can be as simple as a series of IF–THEN–ELSE-type statements that test input data (e.g., a pixel) for certain characteristics (e.g., to be within a range of spectral values) and then follow one of two paths based on the result. Such “expert systems” systematically arrive at a single classification for each pixel by ruling out alternatives based on input data values. This mimics the decision-making processes employed by a field geomorphologist, for example; indeed it is important to note that such systems can also exploit three-dimensional contextual and shape information in the same way a human can. DEMs are therefore a fundamental component of a comprehensively designed (and truly three-dimensional) expert system.

Artificial neural networks (ANNs) aim to process information in a similar way to the human brain, by using a large number of highly interconnected processing elements (neurons) working in parallel to solve a specific problem. The key difference between ANNs and other artificial intelligence techniques is that ANNs learn by example and cannot be designed to perform a specific task in the first instance. ANNs are particularly useful for handling
diverse and nonparametric datasets and for modeling nonlinear relationships, making them a particularly attractive method for mapping glacierized terrain. Nevertheless, the value of the output classification is only as good as the quality of the input data; for ANN techniques to be truly robust they must learn to recognize patterns associated with geomorphometric land surface parameters, such as texture, context, and spatial topology, which can be derived (at least partly) from first-order and second-order DEM analyses (Bishop et al. 2001, 2004).

Fuzzy classification algorithms are able to incorporate inaccurate sensor measurements, vague class descriptions, and imprecise modeling into the analysis (Binaghi et al. 1997, Benz et al. 2003), and can result in accurate portrayals of subpixel mixtures of classes. Fuzzy classification procedures assign values to each pixel representing the pixel’s degree or probability of membership in each class, rather than clustering similar pixels together into a thematic set. The fuzzy approach is analogous to human perception, in which there can be uncertainty even between experts analyzing the same environment. Fuzzy sets are a classification tool in themselves; they can be used alone or incorporated into higher level artificial intelligence techniques such as expert systems; either way it is assumed that there is a priori expert knowledge about the environment under investigation to be able to design fuzzy membership functions. In a similar way to expert systems and ANNs, the addition of a topographic dataset into the classification is fundamental to the accurate identification of glacial landforms through shape and contextual analyses (Schneevoigt et al. 2008).

5.6.3 Object-oriented mapping

Object-oriented mapping describes the segmentation and partitioning of the landscape into discrete spatial entities based upon their geomorphometric characteristics (e.g., slope angle, slope azimuth, curvature and relief; Bishop et al., 2001). These entities represent the lowermost level of a hierarchical landscape structure, which in total describes the supposition of surface processes that comprise the topography of a glacierized landscape (Bishop and Shroder 2000). Therefore, by combining spatial entities at the lowermost level, specific terrain features can be identified; by combining terrain features at the second level, landforms can be identified, and so on. High-quality DEMs are clearly fundamental to this approach, if the spatial entities at the lower end of the hierarchical structure are to be accurately quantified and error propagation through the system is to be avoided. This approach has been successfully employed to accurately delineate the ablation zone of the heavily debris-covered Raikot Glacier in the Nanga Parbat Himalaya, for example (Bishop et al. 2001). Terrain object properties were found to be diagnostic of glacier processes representing glacierization, thereby differentiating glacier topography from other surfaces governed by different surface processes.

Object-oriented mapping can be used as a classification technique in its own right, but it has been shown to be particularly effective when used in combination with ANNs (see above) to classify alpine glacial environments. In this specific context, the procedure may follow five key stages (Raup et al. 2007):

1. Classification of land cover using spectral data and topography.
2. Spatial analysis of imagery to generate geometric, shape, and topological information.
3. Generation of geomorphometric parameters from DEMs.
4. Fusion of data into an object-oriented parameterization scheme.

This hybrid approach appears to reduce error and increase consistency in results when compared with other approaches. Indeed, it is true of all the previously described techniques for glacier mapping that they may yield useful terrain classification in their own right, but they have even greater potential when they are integrated together. Fundamental to their success is the provision of a three-dimensional analysis, however. Topological, contextual, shape, and geomorphometric analyses are limited without the use of a DEM, and numerous studies have demonstrated the need for such three-dimensional properties if fully automated glacier mapping is to be realized (Bishop et al. 2004, Paul et al. 2004b, Bolch and Kamp 2006).

5.7 DISCUSSION

It is clear that digital elevation data derived from stereoscopic airborne and satellite imagery are fundamental to many essential cryospheric applica-
ions, and in particular to deriving glacier statistics for inclusion in global databases. Square-gridded (raster) DEMs are most widely employed by researchers because they provide more realistic terrain representations than data interpolated from topographic maps and are easier to derive and to handle than DEMs derived by radar interferometry or airborne laser scanning. However, they are far from perfect, particularly for detecting the abrupt changes in topography that characterize glacial environments, and the challenge of producing fine-resolution DEM data with low data storage requirements remains an issue. Further, the generation of reliable elevation data at any resolution finer than that offered by the SRTM (90 m) remains problematic for many glacierized areas of the world. This is partly because of persistent cloud cover, particularly in mountain regions, and a lack of ground control data, particularly in areas of political sensitivity. Additionally, SRTM data are static and do not allow for multitemporal analyses. While the recently released G-DEM2 may represent a possible breakthrough in terms of spatial detail (30 m pixel size) and accuracy, elevation values represent the combined period of ASTER operations (2000–2011), so offer no better temporal resolution than the SRTM DEM.

Indeed, it is this variability in data quality that remains the major limiting factor in global glacier mapping and characterization. It has consequences for the type, number, and quality of glacier parameters that can be derived for any given area. Furthermore, it influences the effectiveness of different methods and approaches, and makes the standardization of procedures a challenging task. Ideally, elevation data at resolutions and accuracies comparable with those offered by airborne laser altimetry are required for all glacierized regions of the world. Unfortunately, without a wide-swath spaceborne altimeter, we are many years (if not decades) from being able to achieve such a dataset. Even then, it will raise numerous issues regarding high-density point clouds and preprocessing. Nevertheless, there remains great potential in the use of various approaches, such as the integration of multiple multiscale elevation datasets for deriving multiscale information about a single glacierized catchment, and the use of LiDAR data as accurate ground control for photogrammetric DEM extraction, among others. While novel approaches to deriving glacier parameters have been successful, some are yet to be effectively and comprehensively employed on a regional basis. For example, the geodetic method has been proven a useful tool to assess glacier surface lowering and, subsequently, to produce estimates of mass balance. This work, however, has yet to be systematically conducted in many regions of the world. Further, where independent studies have been carried out using such approaches, they are not always directly comparable because of methodological inconsistencies, or inconsistency in the reporting of data error.

Although remote-sensing sensor technology has advanced significantly in recent years, the challenges of representing topography in high-mountain high-relief regions, and accurately quantifying the error within those topographic data, remain significant. For example, a range of studies have shown that for many glacierized regions of the world (mostly those of moderate relief) the topography can be characterized by ASTER DEMs with an accuracy of ±15–30 m (68% confidence level) after some significant postprocessing, but only to ±60 m (68% confidence) in areas with steep rock headwalls and large low-contrast accumulation areas (Kaëb 2002, Toutin 2008). The issue is complicated further in high-relief mountain areas by slope–aspect error dependence (Bolch 2004), which tends to result in better quality elevation data being derived on slopes facing south (in the northern hemisphere) because of advantageous illumination and sensor–terrain viewing angle. Illumination variations can be compensated for (to a certain degree) using topographic normalization methods, but this itself requires a DEM, which is not always available at this processing step. In terms of error quantification, some standardization of methods is required. Inconsistencies currently exist between studies in the manner in which errors are reported: some studies quote errors to two standard deviations whereas some only quote the RMSE. A limited number do not even quantify the expected error (or uncertainty) in the presented data and, of those that do, the accuracy of data can sometimes be highly dependent on the number and positioning of chosen check points (Toutin 2008). It is often difficult, therefore, for an independent researcher to replicate results, or to establish the exact error analysis that has taken place and how reliable it is.

Where reliable topographic data do exist they can be used very effectively for mapping and change detection studies. First-order geomorphometric parameters have been successfully employed to enhance glacier boundary delineation, calculate sur-
The accurate modeling of glacierized terrain is essential because it plays such a fundamental role in the modulation of atmospheric, Earth surface, and glaciological processes (as well as being shaped by these same processes). The glacial environment, and in particular the glacier surface, is extremely labile; this is especially so at present with major adjustments occurring due to climatic forcing. On a catchment scale, topography governs sediment transport and ice fluxes, collectively influencing glacier erosion. On a more local scale, glacier surface topography can influence debris cover distributions, debris depth, meltwater routing, and supraglacial ponding. Conversely, processes and parameters provide feedback that affects glacier topography—thick debris covers can insulate glacier ice, for example, and meltwater ponds thermally erode ice at their margins and their bases. At the most local level glacial features such as ogives, moraines, seracs, and crevasse fields define the topography of glacier surfaces. It is therefore clear that there is complex two-way interaction between topography and surface processes across a range of spatial and temporal scales that needs to be better understood to inform ideas relating to geomorphological landscape evolution.

The interaction between topography and most geophysical processes occurs over a range of spatial scales, which cannot currently be truly represented within DEM data. Therefore, while the resolution of the generated DEM is limited by the resolution of input source data, scientific interpretations should also be mindful to restrict analyses to the natural scale of the terrain-dependent application. As a guide, the resolution of the derived DEM can provide a practical indication of the scale of information content; analyses of processes or features that occur on a finer scale than this should be made with caution. For example, relatively small-scale features (e.g., moraine ridges) can be entirely missed by medium-resolution datasets, yet may change an interpretation of a process or set of features with their presence. Conversely, with a fine-resolution DEM, analyses made on a coarser scale may be hampered by noise, and indeed a coarser resolution DEM may be more appropriate for use. With constant computational developments, methods for representing fine-scale shape and structure are continually improving and so is the incorporation of terrain structure into considerations of spatial scale. A classic example of this is the development of scale-dependent classification methods, which are increasingly considering terrain hierarchies with the realization that landforms are often not spatially delimited and that one landform may partially comprise another.

Consequently, research on glacier mapping and the extraction of glacier parameters indicates that the integration of topographic information on a variety of spatial scales is important in order to produce reliable results. However, methodologies significantly vary, and some problems remain for high-mountain areas, particularly in change detection studies. For example, surface features must be maintained across the imaged period for accurate elevation datasets to be derived. This depends on there being sufficient optical contrast between the feature and its surroundings as well as the feature being large enough to be resolved given the sensor resolution; and it is also dependent on there being no (or minimal) modification of the feature shape, size, and contrast during the change, or the masking of the feature by snow cover, for example. Further, the magnitude of the change(s) to be detected may not exceed the uncertainty in the method employed. Errors in satellite-derived DEMs of high-relief terrain are particularly problematic; consequently it is unlikely that researchers will be able to reliably detect surface lowering on a timescale of less than a decade. The solution is to either increase the image resolution (and thus accuracy) or to extend the observation period (thus increasing the magnitude of change). The latter solution is becoming increasingly possible as data archives extend with time and new sources of historical data (e.g., Corona; Boleh et al. 2008) emerge. The former issue is aided by the launch of new and improved sensors.
Remote sensing is a constantly advancing discipline, so the launch of a new and/or improved sensor is often imminent and the promise of more accurate or more detailed imagery is never far away. Some of the most promising developments for the generation of new elevation data come from non-optical sources. For example, the recently successful launch of TanDEM-X, the interferometric partner of TerraSAR-X, promises to provide a global DEM to HRTI-3 specifications (Weber et al. 2006; i.e., 12 m spatial resolution, <2 m relative vertical accuracy and <10 m absolute vertical accuracy). These specifications can only currently be achieved by aerial photogrammetry and very fine-resolution optical satellite imagery such as WorldView, but with associated costs. Spaceborne laser altimeters (e.g., GLAS, on board ICESat-1) provide comparable accuracy, but with very limited swath width and low point density, and there is no real prospect of routine collection of such data again until the proposed launch of ICESat-2 in 2015.

If topographic and spectral data are to be truly integrated into surface process modeling, and results compared between independent studies, there is a requirement for a representational framework that scientists can work towards. Currently, scientists employ a range of analytical tools, algorithms, processing approaches, and software for the generation, manipulation, and interpretation of topographic data. Methods are highly empirical, thus the type and quality of the derived data are dependent, to a large extent, on the analyst. Consequently, replication of existing results can be difficult (even more so the application of one published technique to a new area). Standardization and protocols for information extraction and integration are therefore required if data quality, result accuracy, and the validity of comparing measurements across different studies (and study areas) are to be assured.

5.8 CONCLUSIONS

Digital elevation models are fundamental to the extraction of three-dimensional glacier parameters for inclusion in global databases (e.g., WGI, GLIMS, GlobGlacier) as well as for calculating mass balance data, automatically delineating glacier boundaries, modeling surface energy balance and radiation fluxes, characterizing geomorphometry, and analyzing altitudinal-dependent processes. A range of sensors exists that offers data appropriate for the extraction of elevation information, but ASTER remains the most widely used data source because of its stereoscopic capability, wide spectral range, medium-to-fine spatial resolution and, importantly, low cost. The extraction of elevation information from ASTER data performs well in areas with low relief and gently sloping topography, but errors can be large in areas with steep rock headwalls and in areas with low contrast (e.g., fresh snow cover). A range of postprocessing tools can be used to identify and reduce such errors before any secondary analyses are undertaken.

Digital elevation models from nonoptical sources (e.g., LiDAR, InSAR) are becoming increasingly common and can often improve on, or be fused with, existing elevation datasets to enhance cryospheric studies. Such sources have tremendous potential for the extraction of three-dimensional data over glacierized terrain in the future, and in particular for increasing the temporal resolution of change detection analyses, which is currently of the order of a decade or more. However, they may also bring new challenges in terms of handling data volume (particularly in the case of LiDAR point clouds) and in upscaling acquired information, where such detail is not required. For this reason, the development and publication of standard methods (or protocols) for acquiring, processing, and representing digital elevation data will become increasingly important. In the short term, challenges remain in identifying and quantifying altimetric errors, particularly when comparing DEMs from different sources, and in simply gaining access to reliable data for some of the most politically sensitive regions of the world.

5.9 ACKNOWLEDGMENTS

Quincey was funded by a Research Council U.K. Fellowship; Bishop was funded by the National Aeronautics and Space Administration under the NASA OES-02 program (Award NNG04GL84G). ASTER data courtesy of NASA/GSFC/METI/Japan Space Systems, the U.S./Japan ASTER Science Team, and the GLIMS project.

5.10 REFERENCES


