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A review of remote sensing methods for glacier mass balance determination

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Abstract

Airborne and satellite remote sensing is the only practical approach for deriving a wide area, regional assessment of glacier mass balance. A number of remote sensing approaches are possible for inferring the mass balance from some sort of proxy estimate. Here, we review the key methods relevant, in particular to Andean glaciers, discussing their strengths and weaknesses, and data sets that could be more fully exploited. We also consider future satellite missions that will provide advances in our observational capabilities. The methods discussed include observation of elevation changes, estimation of ice flux, repeat measurement of changes in spatial extent, snowline elevation and accumulation–ablation area ratio estimation. The methods are illustrated utilising a comprehensive review of results obtained from a number of studies of South American glaciers, focusing specifically on the Patagonian Icefields. In particular, we present some new results from Glaciar Chico, Southern Patagonian Icefield, Chile, where a variety of different satellite and in-situ data have been combined to estimate mass balance using a geodetic or elevation change approach over about a 25 yr period.

Keywords: satellite remote sensing; Patagonia; Glaciar Chico; mass balance; glacier

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1. Introduction

The Andes of South America are believed to have contributed about 10% of the glacial component of sea level rise during the 20th Century (Rivera et al., 2002). In addition, the region contains the largest ice cap (by area and volume) outside of the polar regions: the Southern Patagonian Icefield (SPI). The SPI, and South American glaciers in general, have been under-represented in global ice mass balance studies, largely because of the lack of data, in particular the absence of a systematic, long term and validated mass balance programme (Dyurgerov and Meier, 1997). To date, systematic field-based, mass balance measurements have only been carried out between 1995 and 1998 on one glacier located near the SPI (Glaciar de Los Tres, 49°20′S, 73°00′W, area 0.976 km^2, length 1.5 km; (Popovnin et al., 1999)). The main basins of the ice cap have been only partially surveyed, allowing general estimations of the mass balance (Casassa et al., 2002), complemented by modelling and SAR interferometry studies (Rott et al., 1998; Forster et al., 1999; Michel and Rignot, 1999), and recently, with the use of a geodetic approach based upon comparison of digital elevation models (DEMs) (Rignot et al., 2003).

Most of the direct measurements of mass balance data of the SPI have been obtained during field campaigns conducted in the lower ablation areas of a few glaciers,

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such as Perito Moreno (Rott et al., 1998), Tyndall (Nishida et al., 1995) and O'Higgins (Casassa et al., 1997). In the accumulation areas, the available data are much more sparse, with a few exceptions for Glaciares Chico (Rivera and Casassa, 2002), Tyndall (Shiraiwa et al., 2002) and Moreno (Aristarain and Delmas, 1993).

Several indirect measurements of glacier characteristics have been obtained for the whole SPI, using remotely sensed satellite data (Aniya et al., 1996; Aniya et al., 1997), but detailed mass balance related analyses only exist for a small number of glaciers including Perito Moreno, (Stuefer, 1999) Pío XI (Rivera and Casassa, 1999), and Penguin (Forster et al., 1999).

Although ground-based, in-situ techniques exist for measuring glacier mass balance (m.b.) they tend to be labour-intensive, expensive and, usually, provide very limited spatial coverage. Logistical and financial constraints generally prohibit sampling more than a handful of glaciers in a region. As a consequence satellite and airborne observations offer the only practical approach of obtaining a statistically representative/meaningful sample of m.b. estimates at a regional scale. It should be stressed, however, that almost all the techniques considered here require some sort of ground control or validation and so remote sensing approaches, rather than negating the need for field studies, generate a direct requirement for them. In this paper, we review the primary satellite and airborne tools and methodologies available for determining directly, or indirectly, some measure of the m.b. The techniques are illustrated with an extensive review of the key remote sensing studies of Patagonian glaciers relevant to m.b. determination.

There are three fundamentally different approaches to determining mass balance remotely, which are discussed below. Their various merits and disadvantages are considered as well as potential future data sets and approaches that could be utilised. We begin with a brief conceptual overview of the three approaches.

1.1. Component approach

First, we consider the component, or flux divergence, approach. Here, the flux of ice crossing some line or "gate", perpendicular to the direction of flow, is compared with the net m.b. (i.e. the accumulation–ablation) of ice upstream of this line. A convenient location to determine ice flux, for glaciers with a floating tongue, is the grounding line (Rott et al., 1998). The data required for this approach comprise: location of the grounding line, ice thickness and surface velocity at this location and integrated m.b. for the upstream catchment area. The location of the GL has been successfully identified using interferometric synthetic aperture radar (InSAR) techniques (discussed in detail later), which have also been used to derive the velocity field (Rignot et al., 1997). Ice thickness can be either obtained from in-situ observations or determined assuming hydrostatic equilibrium for the floating ice and inverting elevation to give thickness, if the ice and water densities are known. Accumulation rates must, in general, be determined from in-situ data. Probably the most successful and comprehensive application of this approach relevant to the Andes was on Moreno glacier, Southern Patagonian Icefield (SPI), where extensive field observations were combined with Shuttle Imaging Radar (SIR-C) data. In addition to determining calving fluxes and mass balance, the analyses of ice dynamics helped identify the factors controlling the stability of the glacier m.b. (Rott et al., 1998). In general, however, this approach has not been widely used in the Andes due to (1) the dearth of adequate measurements of accumulation/ablation; and (2) the fact that most glaciers have a grounded terminus. We will, therefore, in the rest of this paper, focus predominantly on the two remaining techniques, which have been used with greater frequency and generality.

1.2. Proxy measures of mass balance

There are many reasons why direct observations of m.b. are either impractical or too inaccurate to be of value, as discussed later. Thus, it can be useful to measure a proxy variable that is qualitatively or quantitatively related to m.b. The two main approaches are to monitor or track changes in the position of the end of summer snowline (Klein et al., 1999), which is normally close to the equilibrium line altitude (ELA), and/or make repeat observations of changes in areal extent and, in particular, terminus position through time (Aniya et al., 1997; Aniya, 1999; Aniya et al., 2000). If an estimate of ice thickness along the glacier is known then the change in extent can be converted to a change in volume but not without making assumptions about changes in thickness of the remaining ice during the time interval. Recession of a glacier snout is often cited as evidence for a negative mass balance but should, in general, be treated with caution as changes in terminus position may or may not reflect changes in m.b. further up-glacier and, in particular, in the accumulation area. Thus, determining a volume or mass change, integrated over the whole glacier, can be problematic, especially in the case of calving glaciers.

1.3. Geodetic approach

In this approach, a change in mass of the glacier is inferred from a change in elevation over time ($\mathrm{d}h/\mathrm{d}t$)

(Rignot et al., 2003) and has not only been applied to Patagonia but also to many other ice masses including the Greenland and Antarctic ice sheets, Alaskan glaciers, Svalbard ice masses and so on (Wingham et al., 1998; Krabill et al., 2000; Arendt et al., 2002; Bamber et al., 2004). The approach requires accurate elevation measurements from at least two epochs separated by a sufficiently long time to allow the signal to be statistically significant with respect to measurement errors and natural variability in accumulation and ablation. The last point is particularly relevant to Andean glaciers, which can have (particularly in the tropical Andes and Patagonia) high turnover of mass and, consequently, relatively high inter-annual variability. For example, net accumulation rates of 11 and 17.8 m a^{-1} w. eq. were estimated for Glaciar Tyndall, SPI, at the continental ice divide (Shiraiwa et al., 2002).

2. Methods

Having introduced the conceptual framework of the remote mass balance determination we now provide an overview of the techniques and data sets needed. Given the limited space available, this is, inevitably, a summary of the key points and a more detailed discussion of the methodologies can be found elsewhere (Bamber and Kwok, 2003).

2.1. Indirect observations

There are several characteristics of the surface of a glacier that can be derived from remote sensing data and which, in some way, may be useful for determining mass balance. Visible imagery, in particular from Landsat TM/ETM and the Advanced Spaceborne Thermal Emission and Reflection Radiometer, ASTER, (discussed in more detail later), with resolutions of 30 m and 15 m respectively in multi-spectral mode, can be used to determine the end of summer snowline by differentiation between (wet) snow and ice (Bindschadler et al., 2001). Excluding the influence of superimposed ice on the net m.b., the transient snowline altitude (SLA) at the end of the ablation season is a reasonable proxy for the ELA and can, therefore, be used to determine the accumulation area ratio (AAR) of the glacier. This also requires accurate determination of the glacier extent, which, for debris-covered and/or dirty glacier margins is not necessarily straight forward. Nonetheless, within the framework of the Global Land Ice Monitoring from Space (GLIMS) methods for reliable and repeatable ice/land discrimination have been developed for both Landsat ETM and ASTER data (Paul et al., 2002). The major advantage of both these sensors over commercial systems, such as SPOT5, which has 10 m multi-spectral resolution (and 2.5 m panchromatic), is the cost of access to the data for scientific users. If a measurement of AAR can be combined with contemporaneous in-situ data on m.b. from, for example, stake and snowpit observations, it becomes possible to infer quantitative estimates of changes in m.b. from changes in AAR assuming that the m.b. gradient down the glacier does not change significantly. Clearly, a quantitative estimate for one glacier cannot be easily extrapolated to provide regional coverage due to the glacier-specific nature of the in-situ calibration data. Nonetheless, qualitative estimates of changes in m.b. can be made from changes in both AAR and SLA (Klein et al., 1999; Clare et al., 2002). With this approach it is important, however, to assess the inter-annual and shorter-term variability in SLA as the choice of image date can have a significant impact on the estimated SLA. A single day of heavy snow or rain or strong melting, for example, can have a marked impact on the results. Two measurements separated by one or two decades are, therefore, of limited value without some consecutive annual observations to provide an estimate of variability and measurement error (Chinn, 1995).

Both Landsat ETM and ASTER data can also be used to determine surface albedo (Greuell and Knap, 2000). Although this, in itself, cannot provide an estimate of m.b. it is perhaps the single most important input parameter for determining the surface energy balance of a glacier, which, in turn, can be used to model ablation (Lefebre et al., 2003). Data from automatic weather stations and/or a regional meteorological forecast model have, for example, been combined with satellite-derived observations of albedo, to estimate ablation (but not to our knowledge in Patagonia). The key issues that must be tackled here are (1) atmospheric absorption; (2) the bidirectional distribution function of snow and ice (which is not well known); and (3) the conversion from narrow band (as measured by the satellite) to broad band albedo, which requires knowledge of the spectral response of different snowpacks (Stroeve et al., 1997).

Perhaps the most common use of visible (and/or radar) imagery is for the determination of areal extent and, in particular, terminus advance or retreat. This is another indirect estimate of m.b. as a change in area cannot be easily converted to change in mass without information on any concomitant change in ice thickness. For example, a rapid advance or surge type behaviour can increase the ice-covered area without affecting, or possibly even reducing, the overall mass of the glacier (Aniya et al., 2000). In one study, Landsat TM and RADARSAT SAR data were used to map changes in extent of seven glaciers in the SPI. Five of the glaciers were retreating at a fairly similar rate while two had advanced during the same period (Aniya et al., 2000). A more extensive study was undertaken for 48 glaciers in the SPI and 22 from the Northern Patagonian Icefield (NPI) for a period of about 50 yr, from the 1940s onward. Again, although the overall picture was one of retreat, there were some notable exceptions (Aniya, 1999). These examples emphasise that obtaining a representative sample and consideration of ice dynamical effects is essential when making inferences about mass balance from changes in extent. This is particularly true for calving glaciers where changes in terminus position can be rapid and associated with subtle, nonlinear ice dynamical influences (Warren and Aniya, 1999; Skvarca et al., 2003).

2.2. Geodetic methods

The most successful approach for remote quantitative observations is the geodetic approach (Rignot et al., 2003). Strictly, this is not a direct observation of m.b. as it relies on the assumption that a change in elevation (dh/dt) over time can be translated into a change in mass. This is only true if (1) there is no change in elevation of the bedrock due to tectonic activity or post glacial rebound; and (2) the density of the ice mass has not changed. Changes in densification rate of the firn

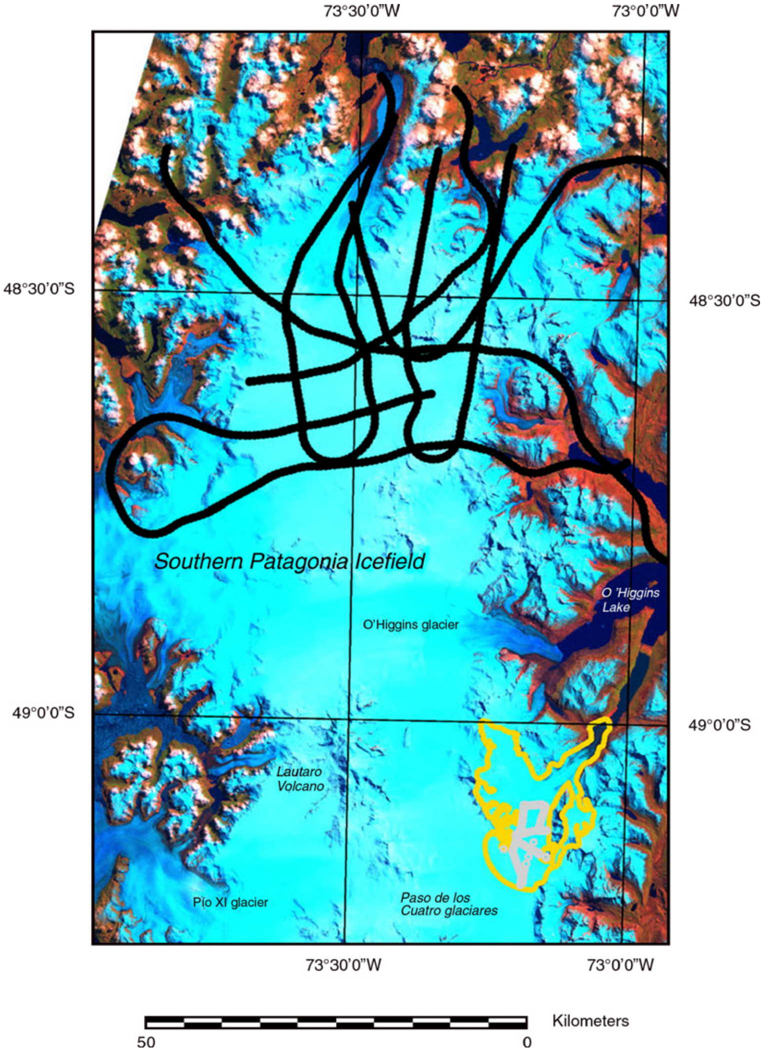

Fig. 1. False colour composite Landsat ETM+satellite image (bands 1, 4 and 5) acquired on October 27, 2000. The outline of the Glaciar Chico basin in 2001 is shown in yellow. Flight lines of the airborne topographic mapper lidar, collected on December 7, 2002, are shown in black. The white circles indicate the location of GPS data collected in September 2001 and used as the reference for the elevation changes plotted in Fig. 2.

layer in the accumulation area are, however, unlikely to exceed a few centimetres per year and bedrock changes are, in general, an order of magnitude smaller still. If the elevation changes observed are in the range of metres/year then these issues are a second order consideration. As mentioned earlier, due to the high inter-annual variability in both accumulation and ablation, a signal on the order of a metre/year or more is typically required for unambiguous interpretation for time intervals less than a decade. The geodetic approach can be split into two data types: point measurements and raster DEMs derived from photogrammetry or interferometric synthetic aperture radar techniques (see later).

2.2.1. Altimetry

The first category of geodetic data relies on spot heights obtained from airborne or satellite laser or radar altimetry or in-situ GPS measurements. Airborne laser altimetry has been successfully used to infer the m.b. of the Greenland ice sheet, Alaskan glaciers, Canadian ice caps and ice masses in Svalbard (Krabill et al., 2000; Arendt et al., 2002; Bamber et al., 2004). At the time of writing, this approach has not been used on any Andean glaciers, although an overflight of glaciers Tyndall and Grey was undertaken in 2001 using a Danish laser system, and the NASA Airborne Topographic Mapper (ATM) (Krabill et al., 1995) over part of the Southern Patagonian Icefield (SPI) in 2002 (Fig. 1). These data provide a high accuracy (10 cm) data set for comparison with future measurements from, for example the Geosciences Laser Altimeter System (GLAS) onboard the Ice Cloud and land Elevation Satellite (ICESat).

ICESat was launched in January 2003 with the aim of providing decimetre accuracy elevation data over the ice sheets, sea ice, ice caps and some larger glaciers. The instrument has a 70 m footprint on the ground and employs a dual frequency laser (green and near infra-red) to enable correction for atmospheric delay effects. The original plan was for a minimum of a 3 yr mission with the satellite placed in a 183-day repeat cycle with an orbit inclination providing coverage up to a latitude of 86°. Unfortunately, problems encountered with the laser sub-system have reduced the operating lifetime and mission capabilities. As a consequence, the satellite has been placed in a 91-day repeat but with only 33 days of coverage per repeat cycle. This results in an across-track spacing at the equator of about 84 km, which is reduced to around 54 km at a latitude of 50°. Along-track spacing of measurements is 172 m.

This means that smaller glaciers may only have one track over them, comprising a handful of measurements. Conventional satellite radar altimetry will not be discussed here as the current fleet of instruments cannot provide usable measurements over ice masses other than the Antarctic and Greenland ice sheets. This situation will be partially remedied with the launch of CRYOSat II (scheduled for the 2010). This satellite will carry two phase sensitive radar altimeters allowing synthetic aperture processing of the data. This will result in a smaller effective footprint and the ability to range to steeper slopes compared with conventional radar altimeters such as those on the European Space Agency ERS and ENVISAT satellites (which were limited to slopes less than about 1°). CRYOSat II aims to provide usable data for ice masses with an area greater than about 10^4 km^2 and should, therefore, obtain measurements of value over parts of the Patagonian Icefields. The final type of spot height measurement that can be utilised for geodetic estimates of m.b. is from in-situ GPS observations. As will be illustrated shortly these can be combined with raster-based DEMs to produce $\mathrm{d}h/\mathrm{d}t$ estimates.

Point measurements tend to be of high accuracy (decimetre) but with relatively poor spatial coverage. Consequently, a limitation of these measurements is the need to interpolate and extrapolate the results to provide an estimate of $\mathrm{d}h/\mathrm{d}t$ for the whole ice mass. DEMs, derived from photogrammetric or interferometric synthetic aperture radar (InSAR) methods can, in principal, overcome this limitation but, in general, at present, cannot offer a level of accuracy achieved from laser altimetry or GPS. The two approaches are, therefore, complementary with one providing high accuracy and the other extensive spatial coverage. This complementarity has been utilised to produce a time series of $\mathrm{d}h/\mathrm{d}t$ for Glaciar Chico, SPI, from a combination of DEMs derived from airborne photogrammetry and in-situ, kinematic GPS data (Fig. 2), for a limited portion of the glacier (Rivera et al., 2005). More extensive

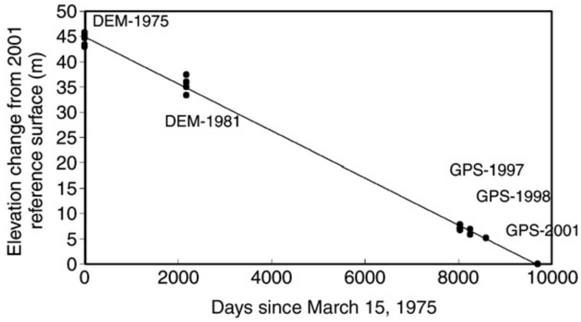

Fig. 2. Elevation change estimates from a combination of airborne photogrammetry and in-situ GPS measurements for Glaciar Chico, Paso Cuatro Glaciares, Chile.

coverage has been produced by using solely, raster-based airborne and satellite-derived data sets (Fig. 3), but at the cost of reducing the temporal sampling due to the limited number of DEMs available.

2.2.2. Photogrammetry

Perhaps the most commonly used approach to deriving DEMs of glaciers has been via the use of aerial stereo photogrammetry. More recently, relatively high-resolution stereo satellite imagery has become readily available for many glaciers, acquired by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). This is an imaging radiometer flown onboard the Terra satellite, launched in December 1999 as part of NASA's Earth Observing System programme. The instrument consists of three different subsystems; the Visible and Near Infrared (VNIR), the Shortwave Infrared (SWIR), and the Thermal Infrared (TIR). The VNIR has a resolution of 15 m and a nadir and backward looking telescope allowing stereo imaging along-track and, thus, the capability to produce DEMs. The accuracy of stereo photogrammetry, given adequate ground control points (GCPs), is approximately equivalent to the pixel size of the sensor. For ASTER this equates to around ±15 m (Kaab, 2002). GCPs, ideally, need to be evenly distributed throughout the image and have decimetre accuracy. This generally requires in-situ GPS observations, limiting the use of photogrammetry to those glaciers that have such measurements available. However, GLAS data may be able to provide adequate height control, although this has not been tested yet and, as mentioned, the coverage may not be adequate for some smaller glaciers. In addition, stereo photogrammetry requires that small segments, or chips, within one image are matched with identical chips in the second image. This is only possible if there is a sufficient variation in albedo within a chip. In the snow-covered, accumulation area of a glacier this is often not the case and the lack of contrast can produce extensive areas without elevation estimates (e.g. Fig. 2, Rivera et al., 2006-this volume). To achieve better accuracies, it is necessary to use either

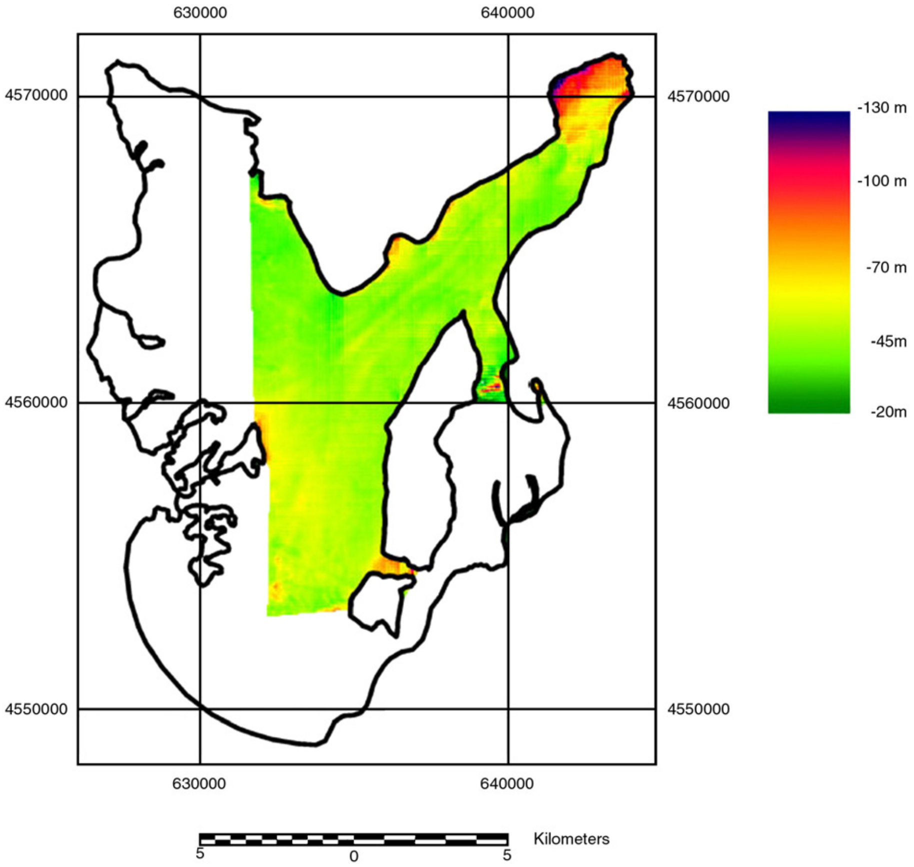

Fig. 3. Spatial pattern of elevation change for Glaciar Chico obtained from SRTM data, acquired in February 2000 and a DEM generated from aerial photographs acquired on March 15, 1975. The 2001 outline of the glacier is shown in black. Co-ordinates are in m, based on the UTM-18S projection.

higher resolution data (e.g. from IKONOS, which has 1 m resolution but is prohibitively expensive or SPOT5, which has 2.5 m resolution but is also expensive) or different technology as discussed next.

2.2.3. Interferometric SAR

The fact that synthetic aperture radars (SARs) record the phase of the returned microwave signal has allowed for the possibility of combining two SAR images taken at different times and/or locations to produce interference patterns caused by differences in phase between coherent points (also termed targets) in the two images. The phase differences are caused by small differences in path length to the target ($r_i - r_j$ in Fig. 4). Combining SAR images in this way is known as interferometric SAR (InSAR) and it has been used extensively since the launch of the first European Remote Sensing Satellite, ERS-1, in 1991, to derive both ice surface motion and topography (Joughin et al., 1995; Joughin et al., 1996). Repeat pass interferometry is where pairs of images taken at different times and slightly different positions are combined. Single-pass interferometry is where two images are recorded at the same time but from different positions.

Differences in path length of a fraction of a wavelength (i.e. millimetres) can be measured from the phase offset between coherent patches of surface in the two images. The interference pattern is a function of (1) the topography ($z(y)$); (2) any displacement of the surface in the look direction, θ, that has taken place between the two image acquisitions ($\mathrm{d}y/\mathrm{d}t$); (3) the separation in space (known as the baseline, B) of the SAR when the two images were acquired (Fig. 4); and (4) in the case of repeat pass interferometry, changes in atmospheric path length between the two dates of acquisition. The displacement component, $\mathrm{d}y/\mathrm{d}t$, of the interferogram is independent of B, but it should be noted that there is no sensitivity to motion that is perpendicular to θ. The sensitivity of the measurements to topography is proportional to the baseline B. For example, if the baseline is zero then there is zero sensitivity to topography and the interference pattern is dependent on displacement only. When the ith and jth observations are acquired at the same time (single-pass interferometry), only the topographic component is relevant.

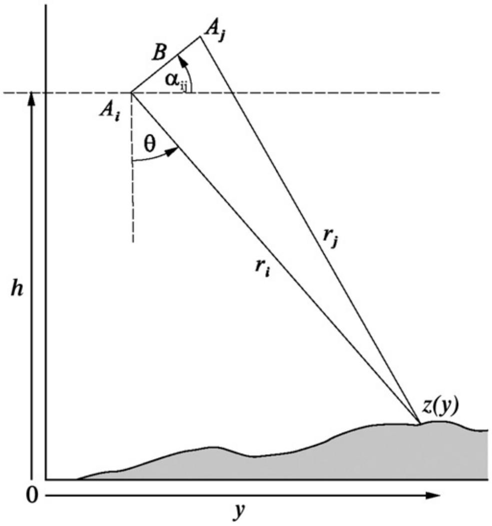

Fig. 4. Schematic diagram showing geometry of interferometric synthetic aperture radar measurements for repeat or single-pass observations.

It should be noted that, as with stereo photogrammetry, InSAR can only provide relative height information and ground control points (GCPs) in the form of either GPS data or a pre-existing (course resolution) DEM are required to: (1) provide absolute height control; (2) improve the baseline estimate, which is crucial to obtain accurate results in the case of repeat pass InSAR; and (3) separate the topographic and motion terms in the phase. It is also possible to achieve (3) by using a combination of more than one interferogram (i.e. from three or more images of the same area) and assuming that the motion term is a constant in all the interferograms generated.

It is evident from the discussion above, that InSAR can provide data to determine ice fluxes needed in the component approach (Rott et al., 1998) or topography that could be used in the geodetic approach. Examples of both tactics exist for Andean glaciers but, as mentioned earlier, the component method is data intensive (and particularly dependent on in-situ m.b. data) and has not, as a consequence, been widely used on Andean glaciers. InSAR-derived velocity data has, however, been used to investigate ice dynamics (Forster et al., 1999; Skvarca et al., 1999). Of greater relevance here is the topographic information present in InSAR data.

To date, one InSAR mission has been flown where deriving topography was the sole objective: the shuttle radar topography mission (SRTM). It involved a short, 11-day flight, in February 2000, specifically designed to map the topography of land surfaces between 60°N and 56°S at a resolution of 30 m for the USA and 90 m elsewhere and with a vertical accuracy of better than 16 m. SRTM deployed two antennas flown on the same platform (i.e. single-pass interferometry) to achieve simultaneous observations with a fixed, known baseline (Rabus et al., 2003; Smith and Sandwell, 2003). For many regions, the accuracy achieved by SRTM was considerably better than 16 m, providing the potential for the use of these data to map lower latitude glaciers and ice caps with sufficient accuracy for elevation change studies. This approach has been nicely demonstrated for the Patagonian icefields using a combination of SRTM and aerial stereo photogrammetry to derive elevation change (dh/dt) estimates over a ~30 yr period (Rignot et al., 2003). In this study, the SRTM data had an accuracy of ±7 m. In a study over the UK, however, the accuracy was found to be nearer ±2 m, although some geo-referencing errors were noted.

Fig. 5. An example of a declassified CORONA satellite photograph of the Southern Patagonian Icefield. The full resolution of the data is quoted as 6 ft (~2 m) and stereo pairs were obtained at 25 ft resolution from February 1962, at 9 ft resolution from August 1963 and 6 ft resolution from September 1967 until May 1972.

DEMs have been produced at 30 m everywhere but are only being distributed at 90 m for regions other than the USA.

3. Discussion

The previous section presented a brief review of the methods available for remotely inferring mass balance. Here we assess the main strengths and weaknesses of the various approaches and attempt to provide a guide to an optimum approach given the various technological, practical and scientific constraints.

For direct observations of m.b. at a regional scale, the geodetic approach would appear to be the most attractive methodology: it can provide a fairly unambiguous measure of mass loss/gain using consistent and extensive observations as was demonstrated for the Patagonian Icefields for example (Rignot et al., 2003). Measured thinning rates during the last few decades, from this study, range from close to zero at high elevation to 5 or 6 m a^{-1} at lower elevations in the ablation zone. A similar, but more detailed study of elevation change has been undertaken on a major glacier draining the SPI (Rivera et al., 2005), where data from aerial photogrammetry were combined with SRTM-derived elevations and in-situ GPS measurements. Fig. 3 shows the observed dh/dt over a 25 yr period for part of Glaciar Chico, SPI. The results indicated a thinning rate of -5.4 ± 0.55 m a^{-1} at the glacier front over this time period and -1.9 ± 0.14 m a^{-1} between 1998 and 2001 for the accumulation area. This latter thinning rate is three times higher than the snow accumulation rate estimated for that part of the glacier (Rivera et al., 2005). A combination of climatic warming, reduced precipitation and ice dynamics are believed to be responsible for these trends.

The error in the dh/dt estimate is the root mean square error (RMSE) of the two measurements. For two DEMs with an accuracy of, say 10 m, the RMSE in dh/dt is ±14 m ($(10^2+10^2)^{1/2}$) and the time interval will, therefore, need to be significantly longer than $dh/dt \times 14$ to provide a meaningful result. In the case of Glaciar Chico, the signal (Fig. 3) is significantly larger than the RMSE, which was estimated to be ±13.8 m (12 m for the photogrammetry and 7 m for the SRTM data). Thus, SRTM can provide contemporary observations with satisfactory accuracy and coverage. The challenge is to obtain adequate historical data. One possible solution to this may be a currently underutilised satellite data set originating from the early 1960s: declassified spy satellite photography. These data are now readily available, at low cost, from the USGS EROS data center.

An example of a CORONA photograph of the SPI, is shown in Fig. 5. Although only available in analogue form (paper prints, negatives or positives), the images have a quoted ground resolution ranging between about 2 and 8 m and provide, in combination with the Landsat archive, a 40 yr temporal record of extent. In addition, stereo pairs were collected from 1962 onward, allowing generation of DEMs with a vertical accuracy of, potentially, 5 m and planimetric accuracy of 3 m. For example, an accuracy of ±10 m was obtained for a test site in Morocco using a standard software package (Altmaier and Kany, 2002). Thus, data from the CORONA satellite program have the potential to provide satellite-based DEMs from as early as the 1960s, with the caveat, that stereo-matching is limited to areas with sufficient contrast and where adequate GCPs are available. It should also be noted, that the coverage over the Andes/Patagonia is not ideal for photogrammetry as much of the data appears to have been collected in the austral winter and spring, when snowcover is a maximum. Some of the images also suffer from cloud contamination. At the time of writing, there are no examples of the application of CORONA data to Andean glaciers although they have been used for glaciological research elsewhere (Bindschadler and Vornberger, 1998). In addition to these data, regular cartographic maps were produced from aerial photography for many parts of the Andes from about 1955–'75 and it may be that these data, although suffering from relatively large errors, might provide a useful historical reference surface if careful characterisation of the errors is undertaken using permanent rock outcrops and other features (Rivera et al., 2005).

There are several missions that will provide, both raster and point, geodetic data in the future including two already mentioned, ICESat (launched in January 2003), and CRYOSat II and a third: TerraSAR. This comprises two separate missions with similar objectives to utilise SAR data for a range of land applications and possibly to incorporate a singe-pass InSAR capability for high-resolution (a few metres) DEM generation (Burbidge et al., 2000; Roth, 2003). TerraSAR-X is an X-band SAR system intended for launch in February 2007 and is a commercially driven project aimed at providing high-resolution (~1 m) imagery over land surfaces (Roth, 2003). TerraSAR-L, is an L-band SAR system being developed by the European Space Agency as a scientific tool for land applications (Burbidge et al., 2000). At the time of writing, the idea of operating one or other of these satellites in a "cartwheel" mode was being considered to allow single-pass, interferometric pairs to be obtained. It seems likely, therefore, that there will be no shortage of suitable geodetic data in the future, although, in the case of InSAR and photogrammetry, adequate GCPs will still be required.

Visible and radar imagery (including aerial photographs), without question, provide the most comprehensive coverage both spatially and temporally of any of the data sets available. There are, however, interpretational difficulties associated with the older, monochromatic, analogue photographs as they offer limited scope for separating, for example, debris-covered ice from unglacierised terrain. The errors in interpretation are likely to be, therefore, higher than say for multi-spectral, fully calibrated, possibly even ortho-rectified, satellite imagery. In addition, to make substantive inferences about changes in m.b. the signal must be both large and extensive. In other words, there must be a consistent trend over the majority of glaciers studied, as discussed earlier, which should be a statistically meaningful sample of the total population of glaciers in a region. It is important, therefore, in studies of historical changes in extent, to quantify the errors in the estimates of area or terminus position, particularly for the earliest records derived from airborne photography. This has rarely been done in the past and makes it difficult to interpret the significance of the results obtained.

So far we have discussed the most effective method for determining the m.b. of a glacier remotely without any consideration of the importance of the interpretation of the results with respect to the underlying mechanism (s) controlling the m.b. There are two components to glacier mass balance: a surface component controlled by accumulation and ablation and a dynamic component controlled by non-linear processes acting within, and at the base, of the glacier. The surface component is most readily susceptible to changes in climatic boundary conditions such as temperature and precipitation. The ice dynamics have a number of controlling factors, which may or may not be related to climate forcing. We have already mentioned the importance of a calving icefront on the dynamic stability of a glacier (Warren and Aniya, 1999) but basal lubrication and hydrology also play an important role on controlling dynamics and, hence, ice flux (Fountain and Walder, 1998). Both the geodetic and indirect approaches provide relatively little direct information on the underlying explanation for a glacier's mass balance. A rapid advance or large calving event may help explain a short-term change but other data, such as repeat velocity measurements and/or climate/meteorological records are generally required to add further insights into the underlying explanation for any observed trend. This is where the component or flux-divergence approach offers a major advantage as it combines surface mass balance with ice dynamic observations allowing, potentially, the separation of the role of the two factors (Rott et al., 1998).

4. Conclusion and outlook

It is clear from the discussion above that no one approach can, currently, provide the necessary spatial and temporal coverage to allow a complete assessment of the m.b. of Andean glaciers. Nonetheless, considerable advances in both our qualitative and quantitative knowledge has been achieved with the aid of satellite remote sensing data sets. The work on this topic, however, is relatively underdeveloped for the Andes and methods developed for Alpine glacier regions have not been extensively applied to glaciers of South America. There is, therefore, scope for considerable progress to be achieved from utilisation of existing remote sensing data sets. The GLIMS project should act as a stimulus for some of this work by providing a baseline data set of both extent and, where possible, elevation for many Andean glaciers. In addition extensive and accurate geodetic data sets have recently become available from SRTM and GLAS, which are providing additional baseline data for observations of elevation change over time. Future interferometric SAR missions, such as TerraSAR (Buckreuss et al., 2003) offer the prospect of high-resolution topographic data derived from InSAR processing. The success and value of data of this type has already been demonstrated for the Patagonian Icefields (Rignot et al., 2003) and it is clear that there is a scope for substantive improvements in our knowledge of satellite-derived glacier mass balance in the near future.

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