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The status of research on glaciers and global glacier recession: a review

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Abstract: Mountain glaciers are key indicators of climate change, although the climatic variables involved differ regionally and temporally. Nevertheless, there has been substantial glacier retreat since the Little Ice Age and this has accelerated over the last two to three decades. Documenting these changes is hampered by the paucity of observational data. This review outlines the measurements that are available, new techniques that incorporate remotely sensed data, and major findings around the world. The focus is on changes in glacier area, rather than estimates of mass balance and volume changes that address the role of glacier melt in global sea-level rise. The glacier observations needed for global climate monitoring are also outlined.

Key words: glacier monitoring, glacier recession, glaciers.

I Introduction

Mountain glaciers and ice caps provide the most readily visible evidence of the effects of climate change, and are, therefore, key variables for early-detection strategies in global climate-related observations. The Intergovernmental Panel on Climate Change has recognized their importance as an overall temperature indicator by including data on glacier fluctuations in all their assessments since 1990 (Houghton *et al.*, 2001).

The twentieth-century recession of most mountain glaciers has widespread ramifications. Glacier melt is responsible for 15–20% of the current rise in eustatic sea level according to Dyurgerov and Meier (1997); it is also important in terms of runoff amount and timing that will affect water resources for agriculture, consumption and hydropower, and it will have significant socio-economic impacts on tourism. Alpine Clubs are already alarmed at the loss of ice climbs (Bowen, 2002), and the scenic impact of disappearing glaciers will affect economies in alpine countries/regions. For example, East African mountains are projected to have no ice remaining within two to three decades. Ice recession will also open up new terrain, facilitate plant and animal migrations (as observed in the Andes and Alps) and expose new mineral resources. Gold mining has been developed in the Tien Shan by massive artificial ice removal, for example. High-altitude ice caps in low latitudes are increasingly suffering melt events. Such ice caps contain important ice-core records of past climate and there is an urgent need to acquire cores from such ice bodies before the records

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are lost (Thompson *et al.*, 1993). Catastrophic events, such as the rock-ice avalanche at Kolka Glacier, northern Ossetia, Russia, in September 2002 (Kotlyakov *et al.*, 2004), and the development and growth of dangerous glacier-dammed lakes, due to the progressive disintegration of debris-covered glacier tongues, as in the Nepal-Bhutan Himalayas and elsewhere, pose major societal risks, as well as economic costs.

There is a rapidly growing literature on glacier changes since the Little Ice Age Maximum (Grove, 2004; Luckman and Villalba, 2001; Solomina, 2000), and during the second half of the twentieth century, based on changes in terminus location and measured mass balances, respectively. Glaciers in low latitudes are rapidly receding (Quarles van Ufford and Sedgwick, 1998; Williams and Ferrigno, 1998a; 1998b; Kaser and Osmaston, 2002), and recent work (Dyurgerov and Meier, 2000; Haeberli and Hoelzle, 1995; Arendt *et al.*, 2003; Meier *et al.*, 2003) suggests accelerated wastage since the late 1970s, especially in the European Alps and Alaska. A similar trend has been identified in the Tien Shan by Dyurgerov *et al.* (1995), Cao (1998), Vilesov and Uvarov (2001), Khromova *et al.* (2003), and others, as well as in other parts of central Asia (Shchetinnikov, 1998). In Patagonia, Rignot *et al.* (2003) report that mass loss from the Patagonian ice fields more than doubled recently.

There have also been substantial advances in modeling glacier response to changes in climate variables in view of the importance of this issue for climate change assessments. This review aims to survey progress in studying the responses of mountain glaciers to climate and to highlight what needs to be done and means to address remaining problems. Glacier dynamics that result from internal processes in the glacier system are not discussed here.

II Glacier characteristics

Mountain glaciers and ice caps outside the two major ice sheets and the Antarctic Peninsula cover some 680,000 km^2 (4.2% of the global ice area), according to Meier and Bahr (1996) and confirmed by Dyurgerov and Meier (1997). The distribution of glacier areas, shown in Table 1, indicates the overwhelming importance of high latitudes. However, the unmeasured area is considerable and hence this estimate is still subject to revision. Also, the time interval to which it refers is not well defined – around 1980 is the approximate date cited by Williams and Ferrigno (1998b) for tabulations in the ongoing 'Satellite image atlas of glaciers of the world' calculations. Estimates of the number of glaciers are equally uncertain – around 170,000 is a suggested number (with 85% of these in the Northern Hemisphere) (Dyurgerov, 2001), but the estimate of glaciers around the Antarctic margins is highly uncertain (Dyurgerov and Meier, 2004). There is a problem with the cut-off used for small-sized ice bodies, which is known to vary between different national and regional inventories. Kääb *et al.* (2002) find that

Table 1 Mountain glacier area by region (after Dyurgerov and Meier, 1997)

Region	Percent of glacier area
Arctic islands	35
Glaciers and ice caps around Greenland and Antarctica	21
Asia	18
Alaska	11
Other USA-Canada	7
S. America, New Zealand, Subantarctic islands	5
Europe	3

glaciers between 0.01 and 1 km^2 in area account for 25% of the glacierized area in the Berne-Valais region of Switzerland. Dyurgerov and Meier (1997) also note that glaciers represent 14–18% of the global sea level rise during the twentieth century and up to 50% more recently, making it important to treat them consistently. Moreover, numerous small glaciers are disappearing over time while large complex glacier systems may fragment into several parts as recession occurs in mountainous terrain and ice divides shift their location.

III Mapping and mass balance measurement

The basic measurements of glacier characteristics as defined for the Global Climate Observing System are length and mass balance (GCOS, 2003). However, glaciologists are also interested in glacier area and volume and their changes, as well as ice velocities. Observations have traditionally relied on field survey of terminus positions, glacier outline, and maximum and minimum elevations, with more recent use of aerial photographs and high-resolution satellite images (Williams and Ferrigno, 1998a; 1998b). Mass balance can be determined by direct and indirect methods. A workshop was held on mass balance measurements in 1998 (Fountain *et al.*,1999) and the results provide numerous examples of standard and new procedures.

The **direct glaciological method** relies on repeated measurements at stakes and snow pits on the glacier surface to determine annual mass balance. The **annual balance** is calculated for fixed dates (eg, 1 October in the Northern Hemisphere) while the **net balance** is the minimum mass at the end of each summer. This definition may be inappropriate for tropical glaciers. Following procedures developed in the 1940s–50s, and documented first by Meier (1962), the stakes are usually arrayed in longitudinal and cross-glacier profiles (Østrem and Brugman, 1991). This may now be combined with high-precision geodetic and photogrammetric techniques for determination of mass and volume changes with high spatiotemporal resolution. However, tests carried out on the Abramov Glacier, Pamir-Alatau, in 1979–80 indicate that a regular network of stakes gives more accurate mass balance data than the usual longitudinal and cross-sectional stake arrays (Kamniansky and Pertziger, 1996). Fountain and Vecchia (1999) show that 5–10 stakes are sufficient for determining mass balance on small (<10 km^2) glaciers and this number seems to be scale invariant up to some unknown limit.

There is a need to determine both winter and summer balances in order to understand glacier changes and their causes. However, long series of such records are few and mainly from Europe (Vincent *et al.*, 2005). Dyurgerov and Meier (1999) note that the summer balance controls the recent negative trend in mass balance with generally little change in the winter balance. However, Dyurgerov (2001; 2003) draws attention to the increase in both winter (positive) and summer (negative) balances indicating intensification of the water cycle with significant mass loss since the end of the 1980s.

The **indirect method** of mass balance determination may involve geodetic determinations that are based on the bedrock as a fixed reference surface, measured from boreholes in the glacier, whereas the direct survey method is referenced to the previous balance year's summer surface. Hubbard *et al.* (2000) combine digital elevation model (DEM) and photogrammetric data with ice flow modeling for analysis of the Haut Glacier d'Arolla.

Several authors note differences between geodetic and glaciological estimates of mass balance (Elsberg *et al.*, 2001; Braithwaite *et al.*, 2002). A number of workshops has been held over the years to examine methods of mass balance determination and the errors involved. Findings of the most recent of these deliberations are reported by Fountain *et al.* (1999). Often, little attention is paid to error assessments, but for the Storglaciären, Sweden, Jansson (1999) finds

that uncertainties in measurements likely translate into uncertainties in the mass balance of about 0.1 m W.E. a^{-1}. Krimmel (1999) compares the direct and geodetic method for the South Cascade Glacier, WA and finds that the latter gave a systematically larger estimate of 0.25 m W.E. a^{-1}. Errors through neglected basal and internal melt due to infiltration (Bazhev, 1997), density assumptions, etc, are estimated to give a total error of only 0.09 m W.E. a^{-1} and the discrepancy is attributed rather to sinking of stakes and the area integration procedure. However, for Hintereisferner, Austria, Kuhn *et al.* (1999) found that the two approaches agreed closely. Sometimes, the hydrological balance (net precipitation minus runoff) has been used to estimate glacier mass balance in heavily glacierized basins. While this approach is usually held to provide only a crude approximation and is not generally recommended, it was used for many years for the basin of the Grosse Aletsch in Switzerland (Kasser, 1967; and subsequent compilations).

Change in glacier length represents an intuitively understood and easily observed phenomenon to illustrate the reality and impacts of climate change. Overall, there are some 800 glaciers where terminus location is monitored every 5–10 years and about 100 of these are long time series (Haeberli, 1998). Terminus location provides a strongly enhanced and easily measured signal of climate change, but at the same time it is indirect, filtered and time delayed. Moreover, some of the larger glaciers in the European Alps have shown only small changes in area, but have thinned considerably, in response to climate change since the late nineteenth century. Nevertheless, Oerlemans (1994) was able to derive an estimate of global warming (0.62 K/100 yr) from changes in the length of 46 glaciers in nine regions over the period 1884–1978, in quite good agreement with observational findings of 0.42–0.53 K/100 yr. The average length change in relation to temperature (Kelvin) was 1.88 km K^{-1}.

Length and area changes can be measured for a great number of ice bodies. Area changes, when coupled with data on ice thickness, are particularly important for calculations of sea-level contributions and of regional hydrological impacts, whereas cumulative length change not only influences landscape evolution and natural hazards (eg, ice- and moraine-dammed lakes) but can also be converted to average mass balance over decadal time intervals and, thus, helps in establishing the representativeness of the few direct mass balance observations. For example, based on 90 glaciers worldwide and a separate set of 68 Swiss glaciers, Hoelzle *et al.* (2003) derive changes in glacier mass balance ($\delta\mathbf{b}$) from length changes via the relation:

$$\delta\mathbf{b} = \mathbf{b}_T \, \delta L/L_0$$

where L_0 is the original length, δL is the change in length, and $\mathbf{b}_T$ is the balance (ablation) at the terminus.

Long-term measurements of glacier mass balance provide direct signals of climate change, without any timelag. However, out of 290 locations with mass balance observations, there are only some 48 series with records spanning more than 20 years worldwide (Haeberli, 1998; Dyurgerov, 2001). A practical procedure to overcome this problem is suggested by Dyurgerov (1996) from analysis of 13 years of mass balance data on the Abramov Glacier. He shows that the mean specific balance can be substituted by the transient balance for one summer and approximated up to the upper limit of the glacier by the glacier's hypsographic curve. The method works best, however, for years with a negative balance. Kamniansky and Pertziger (1996) tested this approach using 23 years of data for the Abramov Glacier and found that the transient snow-line has a closely similar pattern in different years, such that isolines of annual balance are parallel to the firn line.

For change studies, a key glaciological variable is the **equilibrium line altitude**

(ELA), where the annual mass balance is zero, or estimators of it such as; the average of the highest and lowest points on the glacier (known as **Kurowsky's altitude**, k); the **Hess altitude**, H (the height of the contour on a glacier surface, somewhere between the accumulation and ablation zones, that is most nearly straight); or the **glaciation level** (GL) which is the average of the lowest glacierized and highest unglacierized summit in a given region. These parameterizations are discussed by Braithwaite and Müller (1980). For 33 selected glaciers they demonstrated that the average of the maximum and minimum altitude on a glacier is not a suitable indicator of the ELA, whereas the elevation that divides the glacier area into two equal parts is acceptable. Kurowsky defined the area-weighted mean altitude of the glacier. For Axel Heiberg Island glaciers, Cogley and McIntyre (2003) show that all three provide estimates of ELA; however, k is preferable. H is on average ~130 m below the mean ELA, while the GL is 200 m above it. Moreover, k is readily determined from available data. They also estimate that the combined error due to errors in mapping and in map reading by an analyst are about half of the map's contour interval. An important consideration in the determination of regional ELA from small glaciers is the neglect of local deviations that reflect the control of glacier occurrence by local topography. From a study in northern Scandinavia, Carrivick and Brewer (2004) show that a Geographical Information Systems (GIS) approach to ELA determination is essential for representative results.

The **accumulation area ratio (AAR)** is the fraction of a glacier surface that has net accumulation. It is closely related to the vertical profile of mass balance. A landmark study of AAR values for a single year on 475 glaciers in western North America by Meier and Post (1962) showed that values ranged from >0.6 in the Pacific Northwest, where mass budgets were positive, to 0.25–0.5 in the Rocky Mountains of Canada, northwest Montana and the Cascade Range of Washington, where budgets were negative, to <0.2 in the western Alaska Range and the Wyoming Rocky Mountains, where glaciers were stagnant or retreating. For the glacier inventory of the entire former Soviet Union (24,000 glaciers), which is based on surveys spanning mainly the 1960s–70s, Bahr *et al.* (1997) obtain a mean AAR of 0.578 and for 5400 glaciers in the European Alps a value of 0.58. They express the AAR as:

$$\mathrm{AAR} = \left[\frac{1}{(m+1)}\right]^{1/m}$$

For m = 1, AAR = 0.5; for m = 2, AAR = ~0.58; for m = 3, AAR = 0.707.

The conventional AAR value assumed for steady state glaciers is 0.65. Kamniansky and Pertziger (1996) argue that the area accumulation ratio (AAR) is approximately linear with net balance and this is near zero for AAR = 0.65. However, Dyurgerov and Bahr (1999) dispute this finding and suggest rather that the terminus balance is well correlated with the height difference between the mean glacier altitude and the height of the terminus. Such altitude data are readily available in existing glacier inventories and can now be determined from ground-controled ASTER data for example. Xie *et al.* (1996) also determine that the glacier median altitude approximates the 'steady state' equilibrium line altitude (ELA_0) and show that the net balance at this altitude closely corresponds to the mean specific balance of the whole glacier.

Changes in glacier area can be determined using old maps or surveys and recent maps and photographs. Hastenrath (1984) illustrates this for glaciers in equatorial East Africa. Khromova *et al.* (2003) demonstrate the use of a Geographic Information System (GIS) with earlier surveys and high-resolution ASTER satellite data for the Tien Shan. Elsberg *et al.* (2001) examine glaciers in the South Cascades in this way and point out that, while the change in glacier surface elevation is necessary for accurate hydrological

assessments, for most climatic studies determining the change on a static surface is more useful; this is termed a 'reference surface balance'.

The area of ice shown on topographic maps underestimates the true area because small glaciers cannot be depicted. The size of glaciers that are shown depends on the map scale. Kotlyakov *et al.* (1997: 35) state that glaciers 0.1–0.5 km^2 in area (~0.7 km linear dimension) would appear on 1:600,000 (1:50,000) scale maps as lines only 1.5 mm (1.5 cm) long, respectively. These small glaciers are represented on maps of 1:600,000 scale in the *World atlas of snow and ice resources* only by coloring rather than boundary lines. Analysis for a section of the Great Caucasus Range shows that generalization at the 1:500,000 scale leads to a 'loss' of glacier area of 7%. A method to estimate the total area of glaciers (A) in a basin, where the only available information is the mean snow-line altitude and the hypsographic curve of land area, was proposed in the 1970s by Glazyrin and Sokolov (1976):

$$A_{gl} = 0.59\ (\Delta A\ \Delta Z)^{0.93}$$

where ΔZ is the altitude difference between the highest point in the basin and the firn line and ΔA is the basin area above the firn line. The relationship applies where $A \geq 30\ km^2$. For basins in the Amu Darya, Glazyrin (1997) shows that the calculated glacierized area is only 7% less than the measured value reported in the Glacier Inventory. Glazyrin and Sokolov (1976) also noted that the number of glaciers in the basin (N, where $N \geq 50$) can be estimated from:

$$N = 7.4\ (\text{area fraction above the ELA} \times \Delta Z)^{0.56}$$

Subsequently, Glazyrin (1996) used this relationship in an analysis of glacierized basins in the Tien Shan. For actual and calculated values of A_{gl}, there is a correlation coefficient of 0.99 for partly glacierized basins with areas from 30 to 2000 km^2, and correspondingly of 0.87 for basins with between 70 and 1000 glaciers.

IV Glacier response time

Numerous attempts to model the adjustment timescale of glaciers have appeared since the work of Nye (1961), Johanneson *et al.* (1989), McClung and Armstrong (1993), van der Wal and Oerlemans (1995), Boudreaux and Raymond (1997) and Harrison *et al.* (2001). Harrison *et al.* show that when a glacier changes slowly a single timescale can be used. Their timescale includes the effects of surface elevation on net balance rate, which can increase the timescale or give rise to an unstable response. It is worth noting that their time constant determines both the rate and the magnitude of the response to a climate change.

Furbish and Andrews (1984) noted the role of glacier hypsometry in modifying glacier response to similar climate forcing and Haeberli (1990) emphasized the influence of the surface slope of the glacier. This is illustrated by the terminus behavior of 38 glaciers in the North Cascades, Washington, since 1890 (Pelto and Hedlund, 2001). They identified three different response patterns: (i) continuous retreat from the Little Ice Age positions until 1950, followed by an advance until 1976 and subsequent retreat; (ii) rapid retreat from 1890 until 1950 then slow retreat or stable until 1976 and rapid subsequent retreat; (iii) continuous retreat from the 1890s to the present. Despite differences in radiation due to aspect and slope, microclimates are much less important than hypsometry. Type 1 glaciers have steep slopes and extensive crevassing, with high velocities near the terminus. Their response time is 20–30 years. Type 3 glaciers have low slopes, moderate crevassing and low, terminal velocities; their response time is 60–100 years. Type 2 glaciers have intermediate characteristics and response times of 40–60 years.

Hoelzle *et al.* (2003) examine size classes of 90 glaciers worldwide and show that the mass balance change is proportional to

length, which mainly reflects glacier slope. For 68 Swiss glaciers, they identify five slope and size classes and determine changes since about 1900. Long, flat glaciers have undergone constant retreat since the late nineteenth century; valley and mountain glaciers of intermediate size and slope show strong fluctuations with up to three periods of advance and retreat since 1880; steep mountain glaciers show moderate fluctuations and strong individual reactions; flat mountain glaciers have weak fluctuations but a clear overall trend; and very small steep glaciers have high-frequency variability and moderately large amplitudes. The sample of worldwide glaciers shows similar behavior. Overall, since 1900, large glaciers with lengths >8 km show greater losses of mass (-0.25 m a^{-1}) than glaciers <2.5 km (-0.14 m a^{-1}).

V Glacier scaling relationships

Generalized relationships between glacier properties – width, length (L), area (A) and volume (V) – have been developed by Bahr (1997a; 1997b). The general form of these relationships is: $A \propto L^2$ and $V \propto L^3$.

Hypothetically, $V \propto A^{1.5}$, but Bahr *et al.* (1997) find from observations that the exponent is 1.36 for glaciers and 1.25 for ice sheets. For reasonable closure assumptions in the model, the exponent was determined to be 1.375 for glaciers. They developed a physical basis for these relationships from the conservation equations for mass and momentum.

These scaling relationships are extended in the context of global glacier monitoring by Bahr and Dyurgerov (1999). For data from 68 valley and cirque glaciers, they find that balance at the glacier terminus B_T is a function of L^m, where m ~1.7, if L depends on the mass balance, while B_T is a function of area$^{1.09}$. For 303 Eurasian glaciers, Bahr (1997b) found that area $\propto L^{1.6}$ and the later study confirmed this relationship. Bahr and Dyurgerov propose that, in the above power law relating terminal balance and length, m has bounds of 0.5–2.0. They go on to demonstrate for 80 glaciers with data for 1961–90 that, whereas terminus balance is well correlated with mean glacier elevation minus terminus elevation, the correlation between glacier mass balance and ELA on a global (or large region) basis is poor. This latter finding is in contrast to the close relationship that holds for individual glaciers.

VI Process studies and modeling

Ohmura *et al.* (1992) have analyzed the climate at the equilibrium line of some 70 glaciers worldwide, for locations with both glaciological and meteorological measurements. They conclude that the characteristic climate can be determined from data for the three summer months on the free-air temperature at the corresponding atmospheric level, summer precipitation and the sum of net global and net infrared radiation. They show that vertical shifts of the ELA will be linear with a temperature increase or precipitation decrease. A one Kelvin change of summer temperature corresponds to a 300–400 mm precipitation change and, for only 15 glaciers with measurements of radiation, it corresponds to a 7 W m^{-2} change of total net radiation.

An extension of this analysis of free-air temperature and ELA is the approach to assessing glacier ablation and mass balance suggested by Conway *et al.* (1995) for the Pacific Northwest of the United States. They use radiosonde upper-air meteorological sounding data as input to a modeling calculation in order to extend the record of direct mass balance observations. However, these upper air soundings generally only began in the 1950s. Greene *et al.* (1999) develop a relationship between ELA and meteorological data using 52 mid-latitude glacier records in both hemispheres. A best-fit linear model was derived using warm-season freezing level height (Z_{FL} in meters) and cold season precipitation (P_{wi} in mm):

$$ELA = 68 + 1.02\, Z_{FL} - 0.90\, P_{wi}$$

They obtained a coefficient of explained variance of 0.93. When used independently

of one another, Z_{FL} accounted for 89% and P_{wi} for 58% of the total variance. Observed temperature trends in the Swiss Alps (Grand St Bernard) indicate a warming of 0.82 K for 1850–1973 while interpolated precipitation data suggest a 43 mm increase in cold season precipitation. These values translate to a projected ELA rise of 114 m compared with a value of 90 m obtained by Maisch *et al.* (1999) based on past and present estimates of glacier size and hypsography. The height discrepancy between the two approaches may reflect a two-decade response time of the glacier lengths to a transient climate change.

VII Controls of glacier size and mass balance

The geographical controls of glacier size involve the latitude, elevation and proximity to an upwind moisture source. Krenke (1974) discussed the role of these factors in shaping the pattern of current glacierization in the Northern Hemisphere. Hence, the largest glaciers and ice caps are found in southern Alaska, the eastern Canadian Arctic Archipelago, the islands of Svalbard, Novaya Zemlya and Severnaya Zemlya, parts of central Asia, Patagonia, and coastal western Antarctica.

A further important factor is whether the terminus is on land or ends in a freshwater lake or in the sea, such that calving is a major control of mass loss. Calving by glaciers and ice caps (other than from the major ice sheets) is especially important in Patagonia (Warren and Aniya, 1999) and the Eurasian Arctic (Glazovsky, 2003). In the former area, enhanced calving may have accelerated recent thinning of the Southern Patagonia ice field (Rignot *et al.*, 2003), while nearly one quarter of the glacier flux in the Eurasian Arctic is discharged by calving into seawater (Glazovsky, 2003). Here, approximately 3.8 km^3 $year^{-1}$ is iceberg flux, representing 60% of glacier runoff on Franz Josef Land, 80% on Novaya Zemlya, and 75% on Severnaya Zemlya. Additionally, 2.0 km^3 is lost because of the thermal decay and wave abrasion of the ice cliffs. On Svalbard, iceberg calving accounts for 90% of the present negative balance of 4.5 ± 1 km^3 $year^{-1}$ (Dowdeswell and Hagen, 2004). For floating glacier tongues, bottom melting can be very significant also. This has been demonstrated recently for the Petermann Glacier in northern Greenland (Steffen *et al.*, 2003).

The basic factors controlling glacier mass balance are well known, in general (Oerlemans, 2001, for example). They involve firstly climatic conditions – cold season snow accumulation and warm season ablation. Vincent and Vallon (1997) point out that glacier surface albedo is a major control of ablation, and therefore mass balance, and needs to be taken into account for long-term reconstructions of glacier mass balance from climatic data. The usual balance seasons for mid-latitude ice bodies are October–May and June–September in the Northern Hemisphere. However, in high latitudes snowfall may also occur in the 'summer' months, as is also the case in the high mountains of central and southern Asia (Ageta and Higuchi, 1984; Ageta and Fujita, 1996). In the tropical Southern Hemisphere Andes, precipitation usually falls during the climatological summer while the winter is dry and evaposublimation dominates the ablation process (Kaser and Osmaston, 2002).

Using a coupled GCM (ECHAM4), Reichert *et al.* (2001) examine circulation mechanisms associated with mass balance trends for Nigardsbreen, Norway, and the Rhône glacier, Switzerland. They show that the high phase of the North Atlantic Oscillation, which brings winter precipitation, partly explains positive mass balance in Norway during 1980–95, while giving strongly negative balances in the Alps. Pohjala and Rogers (1997) find that winter accumulation in Scandinavia is closely determined by maritime westerly airflow, while in northern Scandinavia the summer balance correlates best with a Norwegian Sea circulation index weighted to the centre in the Barents Sea, rather than with the NAO.

Similar analyses have been made by Meier *et al.* (2003) for net balance data in several regions. They find that winter balances in northern and central Europe correlate best with the Arctic Oscillation (Thompson and Wallace, 1998) while for western North America the correlations are with the Southern Oscillation and Northern Hemisphere air temperatures. In a more direct approach, Rasmussen and Conway (2004) use the NCEP-NCAR reanalysis data on sea-level temperature and 850 mb moisture flux to assess the seasonal net specific balance on two glaciers in western North America and two in southern Alaska.

VIII Indices of glacier sensitivity to climate

There have been a number of empirical and modeling studies of glacier sensitivity to climatic variables. Kuhn (1981) provided one of the first detailed analyses with examples for continental and maritime glaciers. Principal climatic indices of glacier state and change are the ELA and the AAR, discussed above. Oerlemans (1991) analyzed ELA changes on alpine glaciers and found that ELA would rise 116 m (80 m) for a +1 K rise in mean annual (summer) temperature or for a +0.5 m W.E. increase in net mass balance. However, he noted that the relationship breaks down under precipitation regimes different from the European Alps. In mid-latitudes and in the inner tropics, the mean ELA lies below the mean 0°C level in the ablation season, whereas in the subtropics the ELA can be up to 1000 m above the freezing level (Kaser, 2001). Based on the model developed by Kuhn (1981), Kaser examines the sensitivity of the ELA to climate perturbations acting independently. For a 1 K temperature change, he finds an ELA response of 131 m in mid-latitudes and 182 m in the inner tropics, while an accumulation change of 100 kg m^{-2} a^{-1} leads to corresponding ELA changes of 27 m and 8 m, respectively. In areas such as the South Patagonian Icefield, where there are large west–east climate contrasts, the climate controls of mass balance and ELA vary accordingly (Cook *et al.*, 2003). Ablation rate is a strong function of altitude on both western and eastern ides of the icefield, but on the west side both accumulation and ablation are large, whereas on the east side there is less accumulation and summer ablation is the predominant factor.

Using an altitude-dependent mass balance model with data for two small Austrian glaciers, Oerlemans and Hoogendoorn (1990) calculate a 130 m rise in ELA for 1 K annual warming. They also note that the glacier sensitivity is increased by albedo feedback, anticipating the work of Vincent and Vallon (1997). Traditionally, summer temperature and winter accumulation are the two factors taken into consideration, but this separation into distinct winter and summer balances is not always appropriate. An analysis of 18 river basins in the Pamir-Alai where the ELA is between 3600 and 4350 m points to an average loss of 25–30% of the glacierized area per 0.5 K increase in average summer temperature (Glazyrin *et al.*, 2002). This is based on the observation that a 1 K increase in summer temperature leads to a rise of 120–140 m in ELA. A 20% decrease in annual precipitation gives about the same change. They also suggest that the ice loss would be greatest (least) in areas with limited (extensive) glacierization. The river basins examined ranged in glacierized area from about 8 to 30%. Calculating the arithmetic mean of all available ELA data (for about 50 locations in 1965 and around 70 in the 1990s). Dyurgerov and Meier (2004) show a rise in ELA of about 200 m from the mid-1960s to late 1990s. This reflects increasingly negative net mass balances and a decrease in AAR values.

The variation of AAR with climate was noted by Meier and Post (1962), as discussed above. As a non-dimensional number, it is a particularly useful in analysis of glaciers from different geographical regions. For six glacier regions of Eurasia, Bedford *et al.* (1997) prepared frequency histograms of AAR

based on data in the World Glacier Inventory from the former Soviet Union (Figure 1). The histograms are platykurtic in the Arctic with AARs ranging from 0.3 to 0.9, whereas in lower middle latitudes they are more leptokurtic with peaks in the range 0.4–0.8. Generally, AAR values are largest in cold, dry climates and lowest in maritime conditions. Recorded measurements of AAR increased from about 25 in 1965 to 60 or more by the 1990s. The overall arithmetic mean AAR, as well as that based on records five years or more in length, decreased from about 0.6 to 0.5 over this 30-years period according to Dyurgerov and Meier (2004).

Mass balance data provide the basis for developing coupled energy-balance/flow models. Such models have enabled sensitivity studies to be made of the complex feedback effects involved in glacier changes that relate to surface albedo, surface altitude and dynamic response. Braithwaite *et al.* (2002) use a temperature degree-day model of mass balance to assess the sensitivity for 61 ice bodies. They find a range of −0.1 to −1.2 m W.E. $a^{-1} K^{-1}$. Using a grid-based, distributed mass balance model, based on a temperature index melt model, with imposed snow precipitation for a sample of 17 small glaciers, Schneeberger *et al.* (2003) obtained a very similar range of static mass balance sensitivities, namely −0.2 to −1.5 m W.E. $a^{-1} K^{-1}$. The sensitivity is low in dry cold climates with a short ablation season and high in warm, moist climates. The effect of precipitation is only about one-third that of temperature.

Oerlemans and Reichert (2000) propose quantifying the climate sensitivity of the mean specific balance of a glacier by a seasonal sensitivity characteristic (SSC). The SSC is determined from 12 monthly values each of temperature and precipitation. Examples are given for six different glacier systems. In dry climates summer temperature determines SSC, whereas in maritime climates spring and autumn temperature play an important role.

IX Key findings on changes in glacier size

A comprehensive survey of global glacier trends is not yet possible given the limited observations and their incomplete spatial coverage. In particular, there are many surveys of length, but not area, changes. Nevertheless, the major trends are not in doubt (Table 2). The numbers presented reflect the available information so that in some cases only a relative percentage is stated.

1 Recent reductions in ice area

Ice losses are especially well determined for the European Alps. Maisch (2000) estimates an overall decrease of 27% from the mid-nineteenth century to the mid-1970s and losses were even greater in some subregions. Even more striking is the enhanced recession in the Berne-Valais area during 1973–98 (Kääb *et al.*, 2002). Paul *et al.* (2004) digitized outlines of glaciers in the Swiss glaciers inventories of 1973 and 2000. Area changes for all Swiss and Alpine glaciers for 1973–99 are shown in Table 2. They also found an area decrease for 938 Swiss glaciers over 1983–99 of 16%. This rate was seven times that recorded during 1850–1973. In central Asia, several studies suggest rapid recent recession (Dyurgerov *et al.*, 1995; 1996; Khromova *et al.*, 2003). In the latter study, it was recognized that at least 1–7% of the ice cover shown on earlier surveys that did not appear in a September 2001 ASTER image may represent thin ice/snow fields on slopes adjacent to the glaciers that can undergo rapid fluctuations especially in cold, dry regimes. This type of rapid change is evident also from recent work on thin plateau ice caps in the Canadian Arctic Archipelago (Sharp *et al.*, 2003; Braun *et al.*, 2004; Miller *et al.*, 2004). In the headwaters of the Yangtse and Huang He (Yellow) rivers on the Tibetan Plateau, the total glacierized area decreased, respectively, by 1.7% between 1969 and 2000 (most retreat in the 1990s), and 17% between 1966 and 2000 (most retreat in the 1980s) (Table 2) (Yang *et al.*, 2003). The snowline in the latter

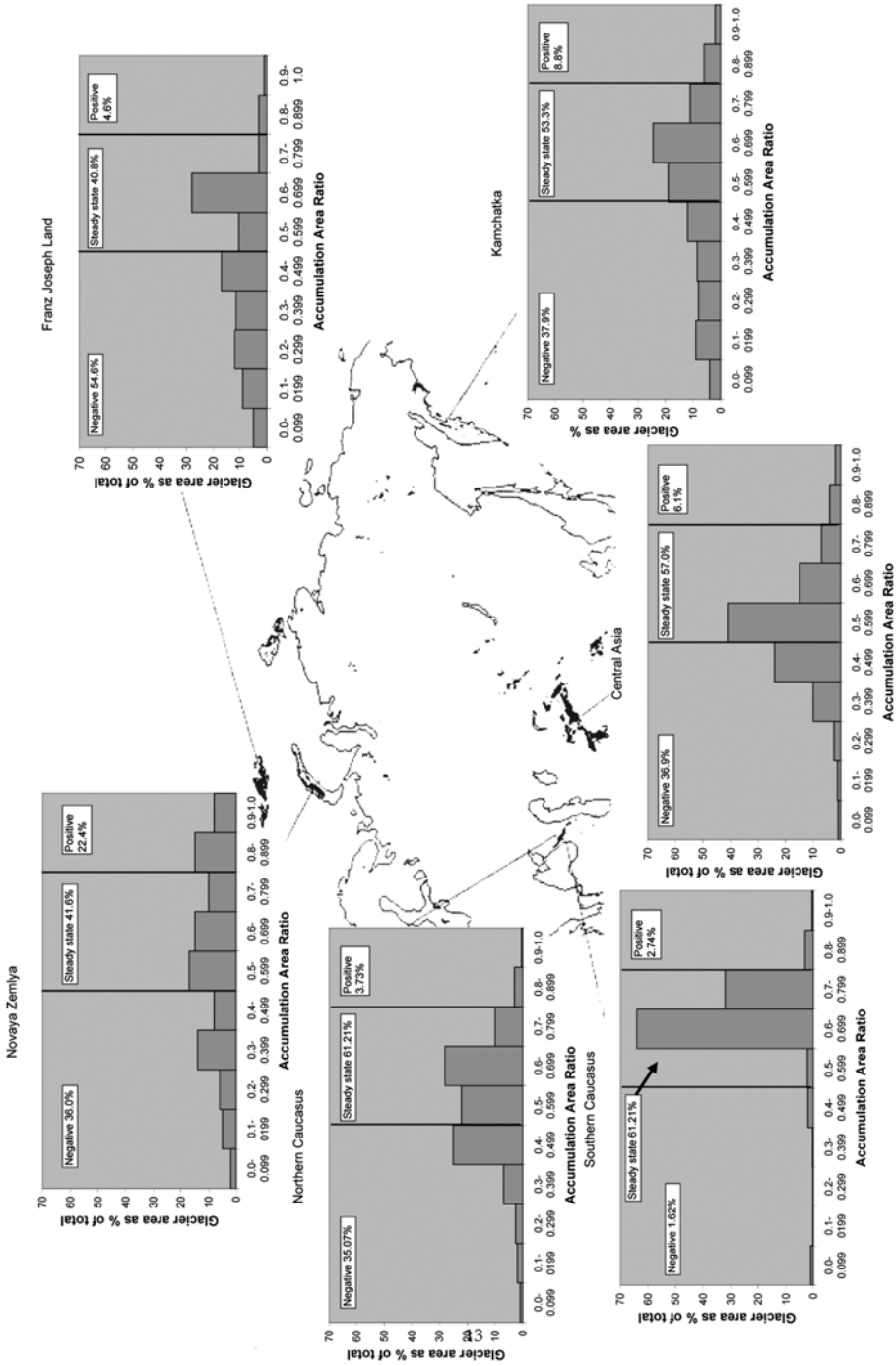

Figure 1 Frequency distributions for accumulation area ratios by region, displayed as percentage of regional glacier area per accumulation area ratio category (locations of regions are shown on the map)

Table 2 Regional and global trends in glacier area

Region	Period	Area decrease (10^3 km^2 and %)		Source
Global	1961–90	6–8	0.9–1.2%	Dyurgerov and Meier (1997)
36 glaciers globally distributed	1961–98	0.034	1.5%	Dyurgerov (2002)
Zailiyskiy-Alatau, Tien Shan	1937–90	0.098		Dyurgerov *et al.* (1996)
Ak-Shirak, Tien Shan	1943–77, 1977–2001	3.4%, 0.043	23%	Khromova *et al.* (2003)
Austria	1969–92			Paul (2002)
Switzerland (300 glaciers, Berne-Valais)	1850–1973, 1973–98		80%, 21%	Kääb *et al.* (2002)
Swiss Alps (2000 glaciers > 0.01 km^2)	1850–1973	0.50	27%	Maisch (2000)
Swiss Alps (2057 glaciers)	1973–99	0.237	18%	Paul *et al.* (2004)
Alpine glaciers (5422 glaciers)	1973–99	0.675	22%	
Western Italian Alps (143 glaciers)	1820–1975	0.112	41.5%	Vanuzzo (2001)
Alaska	1950s–mid-1990s		0.02%/yr	Arendt *et al.* (2003)
Lewis Glacier, Mt Kenya	1899–1993	0.42×10^{-3}	67%	Hastenrath (1984); Hastenrath and Kruss (1992); WGMS (1998)
Kilimanjaro	1912–89		73%	Hastenrath and Greischar (1998)
Antizana 15, Ecuador	1956–98	0.23×10^{-3}	75%	Francou *et al.* (2000)
Chacaltaya, Bolivia	1860–1940	0.3×10^{-3}	58%	Ramirez *et al.* (2001)
	1940–98	0.16×10^{-3}	73%	
North Patagonia Icefield	1945–75	0.9×10^{-3}		Lliboutry (1998)
	1975–96	1.7×10^{-3}		
South Patagonia Icefield	1945–86	0.05		Lliboutry (1998)
Irian Jaya	1936–93	9.0×10^{-3}	69%	Quarles von Ufford and Sedgwick (1998)
Glacier National Park, MT	1850–1993 (or earlier)	16.8×10^{-3}	65%	Fagre (2004)
Queen Elizabeth Islands, Canada	1959–99	1.844	1.8%	Sharp *et al.* (2003)
Størbreen, Norway	1940–97	0.60×10^{-3}	10%	Andreassen (1999)
Polar Urals (2 glaciers)	1953–2000	0.17×10^{-3}	27%	Nossenko and Tzvetkov (2003)
Franz Josef Land	1950s–2000	375×10^{-3}	0.27%	Glazovsky (2003)
Novaya Zemlya		284×10^{-3}	1.20%	
Severnaya Zemlya		65×10^{-3}	0.04%	
Lemon Creek Glacier, Juneau Icefield, AK	1953–98	0.9×10^{-3}	7%	Miller and Pelto (1999)
Athabaska Glacier, Canada	1870–2000	3.4×10^{-3}	57%	Ommanney (2002)

area is 200–385 m lower here than in the more northern Yangtse headwater area.

In equatorial high mountains there are long records from East Africa and western New Guinea. For Mt Kilimanjaro, Hastenrath and Greischar (1998) show that the ice remaining in 1989 was only 27% of that observed in 1912 and the three largest ice bodies had disintegrated. A similar retreat is reported for 1906–90 on the Ruwenzori Range (Kaser and Noggler, 1996). In western New Guinea (Irian Jaya), early photographs have been compared with detailed field studies in 1972 (Hope *et al.*, 1976) and 1992/94, and a 1993 aerial photograph. The glaciers on Puncak Jaya covered 13 km^2 in 1936 and only 4 km^2 in 1993 (Quarles van Ufford and Sedgwick, 1998). They estimate that the ELA rose 60 $\pm$ 10 m since the early 1970s. In the tropical Andes, Ramirez *et al.* (2001) report that Chacaltaya Glacier, Bolivia, had shrunk from an estimated 0.527 km^2 in 1860 to 0.223 km^2 in 1940, and by 1998 was only 0.060 km^2 in area. The volume decrease between 1860 and 1940 was almost sixfold the change in area.

The value of small glaciers as climatic indicators has been both proposed and questioned. Grudd (1990) compared two small glaciers ($<$1 km^2) with two valley glaciers near Tarfala in northern Sweden. He found that the net balances of all four were closely in phase, but the response of the small ones was much greater. One had retreated 700 m since 1915, while the other (which may be frozen to its bed) had thinned. The two valley glaciers have estimated response times of 50–60 years for Storglaciären and 120 years for Rabotsglaciären. Kuhn (1996) argues that the large vertical range of small glaciers relative to their length, the slow horizontal motion relative to annual accumulation, and the fact that ice movement in cirques is by rotational slippage, makes their changes hard to interpret in terms of climate.

In Ellesmere Island, arctic Canada, small plateau ice caps are showing rapid changes. Braun *et al.* (2004) examine two caps near St Patrick's Bay (750–1100 m) and two on Hazen Plateau (900–1100 m). Analysis of a 1:50,000 topographic map from 1959 compared with a GPS survey in 1999/2001 show the ice areas shrank by 30–47%. Based on radiosonde data of freezing level for 1951–2000 from Alert, they suggest ice recession from about 1925 to the early to mid-1960s, followed by a period of mass gain and advance until the early to mid-1970s and subsequent retreat. They suggest the ice caps formed during the Little Ice Age and were still near maximum extent as late as the 1920s.

Marine ice margins reveal the regression trend over the western Russian Arctic in the second half of the twentieth century (Glazovsky, 2003). The largest net recession occurs on Novaya Zemlya (on average -1.5 km, maximum -5.56 km). In second place is Franz Josef Land (on average -0.82 km, maximum -3.6 km) and the last is Severnaya Zemlya (on average -0.13 km, maximum -2.1 km). Because of the general recession of marine ice margins, the ice-covered area on archipelagos has diminished by 725 km^2 (375 km^2 on Franz Josef Land and 284.2 km^2 on Novaya Zemlya).

2 Changes since the Little Ice Age maximum

Changes since the Little Ice Age (LIA) maximum have been examined in several areas of the world but most reports deal with linear retreat from LIA moraines (Luckman and Villalba, 2001, for example, for the western cordilleras of the Americas). For northern Eurasia, Solomina (2000) finds overall that retreat is greater in continental Siberia than in northern Siberia (except for the Pacific rim of Korakskoye Nagorye). However, the timing of the LIA maximum varies between the seventeenth and mid-nineteenth centuries with greater extent in the Caucasus in the thirteenth century. For the Swiss Alps, the ELA rose 90 m on average between 1850 and 1973 according to Maisch *et al.* (1999). They estimated the average ELA using an AAR = 0.67 on a subset of 549 glaciers with unbroken longitudinal profiles. The reduction

in glacier area between 1850 and 1973 was 472 km^2 or 27%. In maritime Norway, the Storbreen in the Jotenheimen had shrunk from the LIA maximum by 16% in 1940 and a further 10% by 1997 (Andreassen, 1999); In New Zealand, Chinn (1998) reported that 127 glaciers in the Southern Alps had lost 25% of their area since the Little Ice Age maximum. However, air photo studies of 111 glaciers over the last two decades found a reversal of the twentieth-century retreat, except for the largest glaciers. Also, small cirque glaciers showed little response to the recent positive mass balances and estimated snow-line lowering of 67 m (Chinn, 1999). Table 2 shows that in equatorial high mountains the ice extent since the end of the Little Ice Age in the mid-late nineteenth century has decreased by 67–75% from the earliest observations and the volume losses are even greater. In southeastern Tibet, in the headwaters of the Yangtse and Haung He (Yellow) rivers, Su and Shi (2002) report that, based on a measured sample of 1139 glaciers, ranging in size from 0.01 to 100 km^2 and representing 13% of the area of monsoonal temperate glaciers, ice that covered 17,124 km^2 in the Little Ice Age maximum (during the seventeenth century) has shrunk by 23% to a current area of 13,202 km^2. Glacier loss since the Little Ice Age maximum up to AD 2000 in the Tibetan areas noted above are 7.2% for the Yangtse and 29.8% for the Huang He headwater areas, according to Yang *et al.* (2003).

3 Recent changes in mass balance

There is now a wealth of studies analyzing regional and global glacier changes, often for slightly different time periods and using different weighting methods. Thus, the mean global net balance can be determined in three main ways (Dyurgerov and Meier, 1997):

(i) an arithmetic mean for all glaciers surveyed;
(ii) an arithmetic mean for 'representative' glaciers having long-term balance data; and
(iii) an area-weighted mean for selected large regions.

It should be noted that the identification of 'representative' glaciers has not been systematically addressed because fewer than 300 glaciers worldwide have mass balance measurements and, of these, time-series data are only available from about 50 glaciers. Hoelzle *et al.* (2003) estimate from length changes in six mountain regions worldwide, that since 1900 there has been a mean balance of -0.25 m W.E. a^{-1}. The average is approximately -0.3 m W.E. a^{-1} for maritime and -0.1 m W.E. a^{-1} for continental regions. Norway and western Canada show the largest losses and the Altai the least. The other two estimates in Table 3 are similar. A definitive summary is probably impossible given the nature of the observations and the incomplete spatial coverage. Nevertheless, the mainly negative trend in mass balance is not in doubt (Table 3) and recent work by Dyurgerov and Meier (2004) shows it to have accelerated on a globally averaged basis since about 1988. To place the volume losses shown in Table 3 in context, the total annual loss for the four regions listed is 96 km^3/year, compared with an estimated loss from Greenland during 1991–2000 of 78 km^3/year (Box and Bromwich, 2004). These values correspond to 0.27 mm and 0.22 mm of sea-level rise, respectively, representing 18% and 15% of the observed rise of 1.5 mm/year.

X Requirements for glacier monitoring

The Second Adequacy Report on the Global Observing Systems for Climate has reaffirmed the importance of glacier observations. (see Haeberli *et al.*, 2000; http://www.wmo.ch/2003). They record a finding that: 'Glacier and ice sheet mass-balance surveys should continue using surface, aerial, and satellite techniques. Geographically representative glaciers should be added to the plans for the future. Countries with data should consider preserving their records in accessible formats and media and

Table 3 Regional and global trends in glacier mass balance

Region	Record period	Mass balance[1]	Source
Global (6 mountain regions)	1900 → 2000	−0.25 m W.E. a^{-1}	Hoelzle *et al.* (2003)
Global (>200 glaciers)	1961–90 (1946–93)	−0.164 (−0.262) (adjusted for bias)	Dyurgerov and Meier (1997)
Global (area-weighted)	1961–76	−0.082	Dyurgerov (2001)
	1977–87	−0.125	
	1988–98	−0.217	
Global (231 glaciers) (1° × 1°grid)	1961–90	−0.23 ± 0.148 m	Cogley and Adams (1998)
W. Antarctic glaciers		−48 ± 14 km^3 a^{-1}	Rignot and Thomas (2002)
E. Antarctic glaciers		+22 ± 23	Rignot and Thomas (2002)
Greenland	1991–2000	−78 km^3 a^{-1}	Box *et al.* (2001)
Alaska	Mid-1950s; mid-1990s	−52 ± 15	Arendt *et al.* (2003)
Patagonia:			
Northern ice field	1968/75–2000	−3.2	Rignot *et al.* (2003)
Southern ice field		−13.5	

[1] The global data are expressed in (m W.E. a^{-1}) which can be converted to global sea-level rise: 0.002826 mm km^{-3}. The regional values are kept in units of volume loss (km^{-3} a^{-1}).

contributing them to archives for future use' (GCOS, 2003).

The World Glacier Monitoring Service (WGMS), and its predecessors, have assembled data on glacier length changes since the late nineteenth century (Haeberli, 2004). Since 1959 they have been published at five-year intervals, the latest being for 1990–2000 (WGMS, 2005).

Monitoring of glacier mass balance internationally already has a 50-year history with records, mostly <10 years in duration, for a total of about 300 glaciers (Dyurgerov, 2001; Braithwaite, 2002). However, there are only some 50 glaciers with record lengths exceeding 20 years and the majority of these are in Europe, North America and the territory of the former Soviet Union. There are also more maritime glaciers among those surveyed than dry, cold ones and there are few large glacier systems.

Modern strategies of worldwide glacier monitoring include the repeated compilation of detailed glacier inventories to obtain global coverage of information about climate change effects. Twenty-five years of coordinated international efforts for the World Glacier Inventory have provided material that enables detailed analyses to be replicated and calculations to be made of the most significant spatial patterns of change for glaciers in various parts of the world (Haeberli, 1998). However, a major task remains to assemble and digitize much additional available information. Moreover, much of the current inventories – documenting close to half of the world's glaciers – remain preliminary and urgently need upgrading with a view to global assessments. Also, the World Glacier Inventory (WGI) contains few specifics for many ice bodies, especially for large glaciers and outlet glaciers associated with ice caps

and ice sheets (see http: //www.geo.unizh.ch/wgms/). Modern techniques should enable this process to be accelerated. For example, a new Swiss glacier inventory has been prepared by Paul *et al.* (2002) using aerial photographs, 1:25,000 topographic map glacier outlines and DEM data in a GIS. Landsat TM and Spot high-resolution imagery was also used for validation. An international project for Global Land Ice Measurement from Space (GLIMS) coordinated by the US Geological Survey is utilizing Landsat and ASTER imagery to map a significant fraction of the world's glaciers and ice caps and to correct the results in a specialized data base established and maintained by the National Snow and Ice Data Center, Boulder (Bishop *et al.*, 2004).

The Global Terrestrial Network for Glaciers (GTN-G), based on century-long worldwide observations, has developed an integrated, multilevel strategy for global observations (http://web/gcos/networks.htm). The GCOS Implementation Strategy calls for measurements of glacier area and mass balance to be made to determine regional volume change at reference sites within each of the major mountain systems worldwide using simple methodologies (index stakes, laser altimetry, repeated mapping). These mountain systems are: Cascade Mountains, USA; Rocky Mountains, Canada; Alaska; Canadian Arctic Archipelago; Equatorial Andes; Svalbard; Russian Arctic Archipelago (Severnaya Zemlya); Scandinavia; European Alps; Caucasus; Altai; Pamir; Kamchatka; Tien Shan; Himalayas; New Zealand Alps; Patagonia; and Mount Kenya. Also individual ice caps in East Greenland and the Subantarctic need to be measured. The GCOS Implementation Strategy states that mass balance measurements of glaciers and ice caps need to be re-initiated in equatorial Africa, Patagonia and New Zealand so that patterns of glacier changes can be monitored globally and data need be provided to the designated data centre. Measurements in the Himalayas need to be expanded.

Sites for long-term observations need to be selected with respect to climate and size/dynamics of the ice body. Meier *et al.* (2003) note that the degree of synchronization of changes in widely separated glaciers depends on their response to changes in atmospheric circulation and related climatic conditions as well as to differences in the glacier dynamics. Recent work by Vincent *et al.* (2004) indicates similar decadal responses over a distance of 300 km from the French Alps to the Tyrol. Extensive glacier mass balance and ice flow studies within major climatic zones will also form the basis for improved process understanding and calibration of numerical models. Glacier inventories based on satellite remote sensing data integrated with digital terrain data in a GIS for automated image analysis, data processing and modeling/interpretation are needed at decadal time intervals. It is planned that each 10-year inventory will be performed by a network of experts in different regions in close cooperation with those space agencies operating high-resolution sensors that can acquire stereographic images.

XI Conclusions

The study of glacier–climate relationships has advanced remarkably since the 1960s, when barely a handful of papers attempted to investigate them. Progress has been made in characterizing glaciers statistically and quantitatively, in quantifying ELA/mass balance relationships, in determining glacier response times, and in modeling glacier sensitivity to climatic variables. The contrast between glacier response in different climatic regimes has also been recognized and defined. Glacier loss is being documented more systematically and attempts to obtain consistent global syntheses are becoming more frequent. Many problems remain, however notably, the currently insurmountable paucity of glacier observations for several key mountain regions of the world and the maldistribution of existing mass balance monitoring sites – in terms of the representation both spatially and for glacier

size classes. An important advance is the recognition by the climate community of the significance of glacier records and the laudable commitment of various funding agencies to support glacier and ice sheet research through both satellite and aircraft missions and field research.

This paper has assembled data on changes in ice extent because this has received less attention than mass loss, which determines sea-level change and is important hydrologically. Area change is fairly readily determined from remote sensing data and is a readily visible element of the landscape. In particular, changes in ice extent affect the local and in some cases the regional surface albedo in summer (when there is little snow cover) and therefore the surface heating. While an assessment of this effect is beyond the scope of this paper, it is a topic that needs to be addressed. Glacier area can be scaled to volume in an overall sense, but it is important to note that glaciers that are frozen to the bed change little in area but may change substantially in thickness. Detection of such change for large glaciers and ice caps is now being undertaken by repeated airborne laser altimetry (Arendt *et al.*, 2003; Abdalati *et al.*, 2004).

XII Postscript

An updated assessment of world glaciers and ice caps indicates a revised total area of 785,000 km^2 and indicates an accelerating contribution of glacier wastage to sea level rise from 0.51 mm/yr for 1951–2003 to 0.93 mm/yr for 1994–2003 (Dyurgerov and Meier, 2005).

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References

Abdalati, W., Krabill, W., Frederick, E., Manizade, S., Martin, C., Sonntag, S., Swift, R., Thomas, R., Yungel, J. and **Koerner, R.** 2004: Elevation changes of ice caps in the Canadian Arctic Archipelago. *Journal of Geophysical Research* 109, F04007, doi: 10.1029/2003JF000045.

Ageta, Y. and **Fujita, K.** 1996: Characteristics of mass balance of summer-accumulation type glaciers in the Himalayas and Tibetan Plateau. *Zeitschrift für Gletscherkunde und Glazialgeologie* 32, 61–65.

Ageta, Y. and **Higuchi, K.** 1984: Estimation of mass balance components of a summer-accumulation type glacier in Nepal Himalaya. *Geografiska Annaler* 66A, 249–55.

Andreassen, L.M. 1999: Comparing traditional mass balance measurements with long-term volume change extracted from topographical maps: a case study of Størbreen glacier in Jotunheimen, Norway, for the period 1940–1997. *Geografiska Annaler* 81A, 467–76.

Arendt, A.A., Echelmayer, K.A., Harrison, W.D., Lingle, C.S. and **Valentine, V.B.** 2003: Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science* 397, 382–86.

Bahr, D.B. 1997a: Global distribution of glacier properties: a stochastic scaling paradigm. *Water Resources Research* 33, 1669–79.

— 1997b: Width and length scaling of glaciers. *Journal of Glaciology* 43(145), 557–62.

Bahr, D. and **Dyurgerov, M.** 1999: Characteristic mass-balance scaling with valley glacier size. *Journal of Glaciology* 45(149), 17–21.

Bahr, D.B., Meier, M.F. and **Peckham, S.D.** 1997: The physical basis of glacier volume – area scaling. *Journal of Geophysical Research* 102(B9), 20, 355–62.

Barry, R.G. 2002: The role of snow and ice in the global climate system: a review. *Polar Geography* 26, 235–46.

Bazhev, A. 1997: Methods determining the internal infiltration accumulation of glaciers. In Kotltakov, V.M., editor *34 Selected papers on main ideas of the Soviet glaciology, 1940s to 1980s*, Moscow: Glaciological Association, Institute of Geography, RAN, 371–81.

Bedford, D.P., Barry, R.G. and **Haggerty, C.** 1997: Analysis of mass balance indicators in the new glacier inventory of the Former Soviet Union. In Colbeck, S.C., editor, *Glaciers, ice sheets and volcanoes: a tribute to Mark F. Meier, Cold Regions Research and Engineering Laboratory (CRREL) Special Report 96–27*, Hanover, NH: US Army, 12–16.

Bishop, M.P., Olsenholler, J.A., Shroder, J.F., Barry, R.G., Raup, B.H., Bush, A.B.G., Copland, L., Dwyer, J.L., Fountain, A.G., Haeberli, W., Kaab, A., Paul, F., Hall, D.K., Kargel, J.S., Molnia, B.F., Trabant, D.C. and **Wessels, R.** 2004: Global land-ice-measurements from space (GLIMS): remote sensing and GIS investigations of the Earth's cryosphere. *Geocarta* 38(129), 233–46.

Boudreaux, A. and **Raymond, C.** 1997: Geometry response of glaciers to changes in spatial pattern of mass balance. *Annals of Glaciology* 5, 407–11.

Bowen, N. 2002: Canary in a coalmine. *Climbing News* 208(90–97), 138-39.

Box, J.E. and **Bromwich, D.H.** 2004: Greenland ice sheet surface mass balance 1991–2000: Application of Polar MM5 mesoscale model and in situ data. *Journal of Geophysical Research* 109, D16105, doi: 10.1029/2003JD004451.

— 2002: Glacier mass balance: the first fifty years of international monitoring. *Progress in Physical Geography* 26, 76–95.

Braithwaite, R.J. and **Müller, F.** 1980: On the parameterization of glacier equilibrium line altitude. In *World Inventory of Glaciers*, International Association of Hydrological Sciences Publication no. 126, 268–71.

Braithwaite, R.J., Zhang, Y. and **Raper, S.C.B.** 2002: Temperature sensitivity of the mass balance of mountain glaciers and ice caps as a climatological characteristic. *Zeitschrift für Gletscherkunde und Glazialgeologie* 38, 63–69.

Braun, C., Hardy, D.R. and **Bradley, R.S.** 2004: Mass balance and area change of four High Arctic plateau ice caps. *Geografiska Annaler* 86A, 43–52.

Cao, M.S. 1998: Detection of abrupt changes in glacier mass balance in the Tien Shan Mountains. *Journal of Glaciology* 44(147), 352–58.

Carrivick, J. and **Brewer, T.R.** 2004: Improving local estimations and regional trends of glacier equilibrium line altitudes. *Geografiska Annaler* 86A, 67–78.

Chinn, T.J. 1998: New Zealand glacier responses to climate change of the past century. *New Zealand Journal of Geology and Geophysics* 39, 415–28.

— 1999: New Zealand glacier response to climate change of the past 2 decades. *Global and Planetary Change* 22, 155–68.

Cogley, J.G. and **Adams, W.P.** 1998: Mass balance of glaciers other than ice sheets. *Journal of Glaciology* 44, 315–25.

Cogley, J.G. and **McIntyre, M.S.** 2003: Hess altitudes and other morphological estimators of glacial equilibrium lines. *Arctic, Antarctic and Alpine Research* 35, 482–88.

Conway, H.L., Rasmussen, A. and **Hayes, P.** 1995: On the use of radiosondes to estimate glacier ablation. *Annals of Glaciology* 21, 245–50.

Cook, K.H., Yang, X.-S., Carter, C.M. and **Belcher, B.N.** 2003: A modeling system for studying climate controls on mountain glaciers with application to the Patagonian icefields. *Climatic Change* 56, 339–57.

Dowdeswell, J.A. and **Hagen, J.O.** 2004: Arctic ice caps and glaciers. In Bamber, J.L. and Payne, A.J., editors, *Mass balance of the cryosphere*, Cambridge: Cambridge University Press, 527–57.

Dyurgerov, M.B. 1996: Substitution of long-term mass balance data by measurements of one summer. *Zeitschrift für Gletscherkunde und Glazialgeologie* 32, 177–84.

— 2001: Mountain glaciers at the end of the twentieth century: global analysis in relation to climate and water cycle. *Polar Geography* 25, 241–336.

— 2002: Glacier mass balance and regime: data of measurements and analysis. Occasional Paper 55, Institute of Article and Alpine Research, University of Colorado., Boulder, 268 pp. Also available at http://instaar.colorado.edu/other/occ_papers.html (last accessed 26 January 2006).

— 2003: Mountain and subpolar glaciers show an increase in sensitivity to climate warming and intensification of the water cycle. *Journal of Hydrology* 282, 164–76.

Dyurgerov, M.B. and **Bahr, D.B.** 1999: Correlations between glacier properties: finding appropriate parameters for global glacier monitoring. *Journal of Glaciology* 45(149), 9–16.

Dyurgerov, M.B. and **Meier, M.F.** 1997: Year-to-hear fluctuations of global mass balance of small glaciers and their contribution to sea level changes. *Arctic and Alpine Research* 29, 392–402.

— 1999: Analysis of winter and summer glacier mass balances. *Geografisker Annaler* 81A, 541–54

— 2000: Twentieth century climate change: evidence from small glaciers. *Proceedings of the National Academy of Sciences* 97, 1406–11.

— 2004: Glaciers and the study of climate and sea-level change. In Bamber, J.L. and Payne, A.J., editors, *Mass balance of the cryosphere. Observations and modeling of contemporary and future changes*, Cambridge: Cambridge University Press, 579–621.

— 2005: Glaciers and the changing Earth system: a 2004 snapshot. Occasional paper 58, Institute of Arctic and Alpine Reasearch, University of Colorado, 117 pp.

Dyurgerov, M., Liu, C.-H. and **Xie Zichu,** editors 1995: *Tien-Shan Glaciers (Oledenenie Tian Shanya)*. Moscow: Publishing House VINITI, 233 pp. (in Russian).

Dyurgerov, M.B., Uvarov, V.N. and **Kostyashkina, T.E.** 1996: Mass balance and runoff of Tyuksu Glacier and the north slope of the Zailiyskiy Alatau Range, Tien Shan. *Zeitschrift für Gletscherkunde und Glazialgeologie* 32, 41–54.

Elsberg, D.H., Harrison, W.D., Echelmayer, K.A. and **Krimmel, R.M.** 2001: Quantifying the effects of climate and surface change on glacier mass balance. *Journal of Glaciology* 47(159), 649–58.

Fagre, D. 2004: Global change research – a focus on mountain ecosystems. NRMSC, US Geological Survey. Retrieved 25 January 2006 from http://www.nrmsc.usgs.gov/research/glacier_retreat.htm

Fountain, A. and **Vecchia, A.** 1999: How many stakes are required to measure the mass balance of a glacier? *Annaler Geografiska* 81A, 563–72.

Fountain, A.G., Jansson, P., Kaser, G. and **Dyurgerov, M.** 1999: Summary of the Workshop on Methods of Mass Balance Measurements and Modelling, Tarfala, Sweden, 10–12 August 1998. *Geografiska Annaler* 81A, 461–65.

Francou, B., Ramirez, E., Caceres, B. and **Mendoza, J.** 2000: Glacier evolution in the Tropical Andes during the last decades of the 20th century: Chacaltaya, Bolivia and Antizana, Ecuador. *Ambio* 24, 416–22.

Furbish, J.J. and **Andrew, J.T.** 1984: The use of hypsometry to indicate long term stability and response of valley glaciers to changes in mass transfer. *Journal of Glaciology* 30(105), 199–211.

Glazovsky, A.F. 2003: Glacier changes in the Russian Arctic. In *Papers and Recommandation: Snow Watch 2002 Workshop and Assessing Global Glacier Recession, Glaciological Data Report GD-32*, Boulder, CO: NSIDC/WDC for Glaciology 78–82.

Glazyrin, G.E. 1996: The reaction of glaciers in west Tien Shan to climate changes. *Zeitschrift für Gletscherkunde und Glazialgeologie* 32, 33–39.

— 1997: Calculation of glacierization response of Soviet Central Asia to potential climate changes. In Kotltakov, V.M., editor, *34 Selected papers on main ideas of the Soviet glaciology, 1940s to 1980s,* Mascow: Glaciological Association, Institute of Geography, RAN, 382–87.

Glazyrin, G.E. and **Sokolov, L.N.** 1976: Raschyot pribilizit'nogo chisla i ploshchadi lednikov v neizuchenykh raionoakh (Calculation of the approximate number and area of glaciers in unstudied regions). *Materialy glyatsiologicheskikh Issledovaniy. Khronika* no. 26. Moscow: Institute of Geography, 97–101.

Glazyrin, G., Braun, L.N. and **Shchettinnikov, A.S.** 2002: Sensitivity of mountain glacierization to climate changes in central Asia. *Zeitschrift für Gletscherkunde und Glazialgeologie* 38, 71–76.

Global Observing System for Climate (GCOS) 2003: *The Second Report on the Adequacy of the Global Observing System for Climate in support of the UNFCCC*. GCOS 82 (WMO/TD no. 1143), Geneva.

Greene, A.M., Broecker, W.S. and **Rind, D.** 1999: Swiss glacier recession since the Little Ice Age: reconciliation with climate records. *Geophyical Research Letters* 26, 1909–12.

Grove, J.M. 2004: *Little Ice Ages, ancient and modern*. London: Routledge, 718 pp.

Grudd, H. 1990: Small glaciers as sensitive indicators of climate fluctuations. *Geografiska Annaler* 72A, 119–25.

Haeberli, W. 1990: Glacier and permafrost signals of 20th-century warming. *Annals of Glaciogy* 14, 99–101.

— 1998: Historical evolution and operational aspects of worldwide glacier monitoring. In Haeberli, W., Hoelzle, M. and Suter, S., editors, *Into the second century of worldwide glacier monitoring – prospects and strategy*, Studies and Reports in Hydrology, Paris: UNESCO, Paris, 35–51.

— 2004: Glaciers and ice caps: historical background and strategies of world wide monitoring. In Bamber, J.L. and Payne, A.J., editors, *Mass balance of the cryosphere*, Cambridge: Cambridge University Press, 559–78.

Haeberli, W. and **Hoelzle, M.** 1995: Application of inventory data for estimating characteristics of regional climate change effects on mountain glaciers – a pilot study with the European Alps. *Annals of Glaciology* 21, 206–12.

Haeberli, W., Cihlar, J. and **Barry, R.G.** 2000: Glacier monitoring within the Global Climate Observing System. *Geografiska Annaler* 31, 241–46.

Harrison, W.D., Elsberg, D.H., Echelmayer, K.A. and **Krimmel, R.M.** 2001: On the characterization of glacier response by a single time-scale. *Journal of Glaciology* 47(159), 659–64.

Hastenrath, S. 1984: *Glaciers of equatorial East Africa*. Dordrecht: D. Reidel, 353 pp.

Hastenrath, S. and **Greischar, L.** 1998: Glacier recession on Kilimanjaro, East Africa, 1912–1989. *Journal of Glaciology* 43(145), 455–59.

Hastenrath, S. and **Kruss, P.D.** 1992: Greenhouse indicators in Kenya. *Nature* 355(6360), 503–504.

Hoelzle, M., Haeberli, W., Dischl, M. and **Pesche, W.** 2003: Secular glacier mass balances derived from cumulative glacier length changes. *Global and Planetary Change* 36, 295–306.

Hope, G.S., Peterson, J.A., Radok, U. and **Allison, I.** 1976: *The equatorial glaciers of New Guinea*. Rotterdam: Balkema, 244 pp.

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P., Dai, X., Maskell, K. and **Johnson, C.,** editors 2001: *Climate change 2001. The scientific basis.* Cambridge: Cambridge University Press.

Hubbard, A., Willis, I., Sharp, M., Nienow, P., Mair, D. and **Hubbard, B.** 2000: Glacier mass balance determination by remote sensing and high resolution modelling. *Journal of Glaciology* 46, 491–98.

Jansson, P. 1999: Effect of uncertainties in measured variables on the calculated mass balance of Storglaciaren. *Geografiska Annaler* 81A, 633–42.

Johanneson, T., Raymond, C. and **Waddington, E.** 1989: Time-scale for adjustment of glaciers to changes in mass balance. *Journal of Glaciology* 35(121), 355–69.

Kääb, A., Paul, F., Maisch, M., Kellenberger, T. and **Haeberli, W.** 2002: The new remote sensing-derived Swiss glacier inventory: II. First results. *Annals of Glaciology* 34, 362–66.

Kamniansky, G.M. and **Pertziger, F.L.** 1996: Optimization of mountain glacier mass balance measurements. *Zeitschrift für Gletscherkunde und Glazialgeologie*, 32, 167–75.

Kaser, G. 2001: Glacier – climate interaction at low latitudes. *Journal of Glaciology* 47(157), 195–204.

Kaser, G. and **Noggler, B.** 1996: Glacier fluctuations in the Ruwenzori Range (East Africa) during the 20th century. A preliminary report. *Zeitschrift für Gletscherkunde und Glazialgeologie* 32, 109–17.

Kaser, G. and **Osmaston, H.**, editors 2002: *Tropical glaciers*. Cambridge: Cambridge University Press, 207 pp.

Kasser, P., compiler 1967: *Fluctuations of glaciers (FoG) 1959–1965, volume I*. IAHS(ICSI)-UNEP-UNESCO, Permanent Service on the Fluctuations of Glaciers, IUGG-FAGS/ICSU, Zurich, 52 pp.

Khromova, T.E., Dyurgerov, M.B. and **Barry, R.G.** 2003: Late-twentieth century changes in glacier extent in the Ak-sirak Range, central Asia, determined from historical data and ASTER. *Geophysical Research Letters* 30(16), 1864, HLS 2-1–2-5.

Kotlyakov, V.M., Grosswald, M.G., Davidovich, N.V., Dreyer, N.N. and **Rototaevea, O.V.**, editors 1997: *World atlas of snow and ice resources, volume II*. Moscow: Institute of Geography, Russian Academy of Sciences, 372 pp.

Kotlyakov, V.M., Rototaeva, O.V. and **Nosenko, G.** 2004: The September 2002 Kolka glacier catastrophe in North Ossetia, Russian Federation: evidence and analysis. *Mountain Research and Development* 24, 78–83.

Krenke, A.N. 1974: Climatic existence conditions for glaciers and the shaping of glacial climates. In Danilina, I.P. and Kapitsa, A.P., editors, *Meteorology and climatology, volume I*, Boston, MS: G.K. Hall and Co., 179–224.

Krimmel, R. 1999: Analysis of difference between direct and geodetic mass balance measurements at South Cascade Glacier, Washington. *Geografiska Annaler* 81, 653–58.

Kuhn, M. 1981: Climate and glaciers. In *Sea level, ice and climatic change (Symposium at Canberra, 1979)*, International Association of Hydrologic Sciences Publication no. 131, 3–20.

— 1996: The mass balance of very small glaciers. *Zeitschr Zeitschrift für Gletscherkunde und Glazialgeologie* 31, 179–91.

Kuhn, M., Dreiseitl, E., Hofinger, S., Markl, G., Span, N. and **Kaser, G.** 1999: Measurements and models of the mass balance of Hintereisferner. *Geografiska Annaler* 81A, 541–54.

Lliboutry, L. 1998: Glaciers of the wet Andes. In Williams, R.S. Jr. and Ferrigno, J.G., editors, *Satellite image atlas of glaciers of the world, South America*, US Geological Survey Professional Paper 1386I, I 148–206.

Luckman, B.H. and **Villalba, R.** 2001: . Assessing the synchroneity of glacier fluctuations in the Western Cordillera of the Americas during the last millennium. In Markgraf, V., editor, *Inter-hemispheric climatic linkages*, San Diego, CA: Academic Press, 119–40.

Maisch, M. 2000: The longterm signal of climate change in the Swiss Alps. Glacier retreat since the Little Ice Age and future ice decay scenarios. *Geografia Fisica e Dinamica Quaternaria* 23, 139–52.

Maisch, M., Wipf, A., Deneler, B., Battaglia, J. and **Benz, C.** 1999: *Die Gletscher der Schweizer Alpen*. NFP-31 (Teil-projekt no. 4031-033412), University of Zurich, Hochschulverlag AG, ETH Zurich, 385 pp.

McClung, D.M. and **Armstrong, R.L.** 1993: Temperate glacier response time from field data. *Journal of Glaciology* 39, 323–26.

Meier, M.F. 1962: Proposed definitions for glacier mass budget terms. *Journal of Glaciology* 4, 252–61.

Meier, M.F. and **Bahr, D.B.** 1996: Counting glaciers: use of scaling methods to estimate the number and size distribution of the glaciers of the world. In Colbeck, S.C., editor, *Glaciers, ice sheets and volcanoes: a tribute to Mark F. Meier*, US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, CRREL Special Report 96–27, 89–94.

Meier, M.F. and **Post, A.** 1962: Recent variations in mass net budgets on glaciers in western North America. *Symposium of Ogergurgl. Variations of the regime on existing glaciers*. International Association of Hydrological Sciences Publication 58, 63–77.

Meier, M.F., Dyurgerov, M.B. and **McCabe, G.J.** 2003: The health of glaciers: recent changes in glacier regime. *Climatic Change* 59, 123–35.

Miller, G., Briner, J. and **DeVogel, S.** 2004: The rapidly disappearing plateau ice caps of Central Baffin Island: where will it all end? 34th *Annual International Arctic Workshop, Abstracts*, INSTAAR, Boulder, CO: University of Colorado.

Miller, M.M. and **Pelto, M.S.** 1999: Mass balance measurements on the Lemon Creek Glacier, Juneau Icefield, Alaska 1953–1998. *Geografiska Annaler* 81A, 671–81.

Nossenko, G. and **Tzvetkov, D.G.** 2003: Assessments of glacier change in the Polar Urals from ASTER. In *Papers and Recommendations: Snow Watch 2002 Workshop and Assessing Global Glacier Recession, Glaciological Data Report GD-32*, Boulder, CO: NSIDC/WDC for Glaciology, 82–83.

Nye, J.F. 1961: The influence of climatic variations on glaciers. *International Association of Scientific Hydrology, General Assembly Helsinki*. IASH Publication 54, 397–404.

Oerlemans, J. 1991: A model for surface mass balance of ice masses. Part I, Alpine glaciers. *Zeitschrift für Gletscherkunde und Glazialgeologie* 27: 63–83.

— 1994: Quantifying global warming from the retreat of glaciers. *Science* 264, 243–45.

— 2001: *Glaciers and climate change*. Lisse, Netherlands, A.A. Balkema, 148 pp.

Oerlemans, J. and **Hoogendorn, N.C.** 1990: Mass-balance gradients and climate change. *Journal of Glaciology* 35(121), 399–405.

Oerlemans, J. and **Reichert, B.K.** 2000: Relating glacier mass balance to meteorological data by using seasonal sensitivity characteristics. *Journal of Glaciology* 46(152), 1–6.

Ohmura, A., Kasser, P. and **Funk, M.** 1992: Climate at the equilibrium line of glaciers. *Journal of Glaciology* 38(130), 397–411.

Ommanney, C.S.L. 2002: Glaciers of the Canadian Rockies. In Williams, R.S. Jr and Ferrigno, J.G., editors, *Satellite image atlas of glaciers of the world, North America*. US Geological Survey Professional Paper 1386J, J 199–289.

Østrem, G. and **Brugman, M.** 1991: *Balance measurements. A manual for field and office work*. NHRI Science Report 4, Ministry of Supply and Services, Canada, 224 pp.

Paul, F. 2002: Changes in glacier area in Tyrol, Austria, between 1969 and 1992 derived from Landsat 5 Thematic Mapper and Austrian glacier inventory data. *International Journal of Remote Sensing* 23, 787–800.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T. and **Haeberli, W.** 2002: The new remote sensing-derived Swiss glacier inventory: I. Methods. *Annals of Glaciology* 34, 355–61.

— 2004. Rapid disintegration of Alpine glaciers observed with satellite data. *Geophysical Resarch Letters* 31(21), L21402, doi: 10.1029/2004GL020815.

Pelto, M.S. and **Hedlund, C.** 2001: Terminus behavior and response time of North Cascade Glaciers, Washington, USA. *Journal of Glaciology* 47(158), 497–506.

Pohjala, V.A. and **Rogers, J.C.** 1997: Atmospheric circulation and variations in Scandinavian glacier mass balance. *Quaternary Research* 47, 29–36.

Quarles van Ufford, A. and **Sedgwick, P.** 1998: Recession of the equatorial Puncak Jaya Glaciers (~1825 to 1995), Irian Jaya (western New Guinea), Indonesia. *Zeitschrift für Gletscherkunde und Glazialgeologie* 34, 131–40.

Ramirez, E., Francou, B., Ribstein, P., Descloitres, M., Guérin, R., Mendoza, J., Gallaire, R., Pouyaud, B. and **Jordan, E.** 2001: Small glaciers disappearing in the tropical Andes. A case study in Bolivia: Glaciar Chacaltaya (16°S). *Journal of Glaciology* 47, 187–94.

Rasmussen, L.A. and **Conway, H.** 2004: Climate and glacier variability in western North America. *Journal of Climate* 17, 1804–15.

Reichert, B.K., Bengtsson, L. and **Oerlemans, J.** 2001: Midlatitude forcing mechanisms for glacier mass balance investigated using general circulation models. *Journal of Climate* 14, 3767–84.

Rignot, E. and **Thomas, R.H.** 2002: Mass balance of polar ice sheets. *Science* 297, 1502–506.

Rignot, E., Rivera, A. and **Casassa, G.** 2003: Contribution of the Patagonia icefields of South America to sea level rise. *Science* 302, 434–37.

Schneeberger, C., Blatter, H., Abe-Ouchi, A. and **Wild, M.** 2003: Modelling changes in the mass balance of glaciers in the Northern Hemisphere for a transient $2 \times CO_2$ scenario. *Journal of Hydrology* 282, 145–63.

Sharp, M.J., Copland, L., Filbert, K., Burgess, D. and **Wiiliamson, S.** 2003: Recent changes in the extent and volume of Canadian Arctic glaciers. In *Papers and Recommendations: Snow Watch 2002 Workshop and Assessing Global Glacier Recession, Glaciological Data Report GD-32*, Boulder CO: NSIDC/WDC for Glaciology, 70–72.

Shchetinnikov, A.S. 1998: *Morfologiya i rezhim lednikov Pamiro-Alaya (The morphology and regime of Pamir-Alai glaciers)*. Tashkent: Central Asia Hydro Meteorological Institute, 219 pp. (in Russian).

Solomina, O. 2000: Retreat of mountain glaciers of northern Eurasia since the Little Ice Age maximum. *Annals of Glaciology* 31, 26–29.

Steffen, K., Huff, R.D., Cullen, N., Rignot, E., Stewart, C. and **Jenkins, A.** 2003: Channel-like bottom features and high bottom melt rates of Petermann Gletscher's floating tongue in northwestern Greenland (abstract). *EOS* 84(46), F370.

Su, Z. and **Shi, Y.-F.** 2002: Response of monsoonal temperate glaciers to global warming since the Little Ice Age. *Quaternary International* 97–98, 123–31.

Thompson, D.W.J. and **Wallace, J.M.** 1998: The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters* 25, 1297–300.

Thompson, L.G., Mosley-Thompson, E., Davis, M., Lin, P.N., Yao, T., Dyurgerov, M. and **Dai, J.** 1993: 'Recent warming': ice core evidence from tropical ice cores with emphasis on central Asia. *Global and Planetary Change* 7, 145–56.

van der Wal, R.S.W. and **Oerlemans, J.** 1995: Response of valley glaciers to climate change and kinematic wave: a study with a numerical ice flow model. *Journal of Glaciology* 1(137), 142–52.

Vanuzzo, C. 2001: The glacier retreat in Val d'Aosta (western Italian Alps) from the Little Ice Age to the second half of the 20th century: linear, areal, volumetric and Equilibrium Line Altitude changes. *Geografia Fisica e Dinamica Quaternaria* 24, 99–113.

Vilesov, E.N. and **Uvarov, V.N.** 2001: *Evolyutsiya sovremenngo oledeneniya Zailiyskogo Alatau v XX veke (The evolution of modern glaciation of the Zailiyskiy Alatau in the 20th century)*. Almaty, Kazakh State University, 252 pp. (in Russian).

Vincent, C. and **Vallon, M.** 1997: Meteorological controls on glacier mass balance: Empirical relations suggested by measurements on Glacier de Sarennes, France. *Journal of Glaciology* 43, 131–37.

Vincent, C., Kappenberger, G., Valla, F., Bauder, A., Funk, M. and **Le Meur, E.** 2004: Ice ablation as evidence of climate change in the Alps over the twentieth century. *Journal of Geophysical Research* 108, D10104, 1–9.

Vincent, C., Ribstein, R., Favier, V., Wagnon, P., Francou, B., Le Meur, E. and **Six, D.** 2005: Glacier fluctuations in the Alps and in the tropical Andes. *Comptes rendus, Geoscience de l'Academie des Sciences* 337, 97–106.

Warren, C. and **Aniya, M.** 1999: The calving glaciers of southern South America. *Global and Planetary Change* 22, 59–77.

Williams, R.S. Jr and **Ferrigno, J.**, editors 1998a: Satellite image atlas of glaciers of the world. US Geological Survey Professional Paper 1386-A.

— editors 1998b: Satellite image atlas of glaciers of the world. South America. US Geological Survey Professional Paper 1386-I, 206.

World Glacier Monitoring Service (WGMS) 2005: *Fluctuations of glaciers 1995–2000 (volume VIII)* (compiled by W. Haeberli, M. Zemp, R. Frauenfelder and A. Kääp. University of Zurich, 296 pp.

Xie, Z., Ding, L., Liu, Ch. and **Liu, S.** 1996: Mass balance at the steady state equilibrium line altitude and its application. *Zeitschrift für Gletscherkunde und Glazialgeologie* 32, 129–35.

Yang, J.-P. Ding, Y.-J., Chen, R.-Sh., Li, S.-Y. and **Lu, A.-X.** 2003: Causes of glacier change in the source regions of the Yangtze and Yellow rivers on the Tibetan Plateau. *Journal of Glaciology* 49(167), 539–46.