Geo Factsheet

www.curriculum-press.co.uk Number 367

Glacial Mass Balance

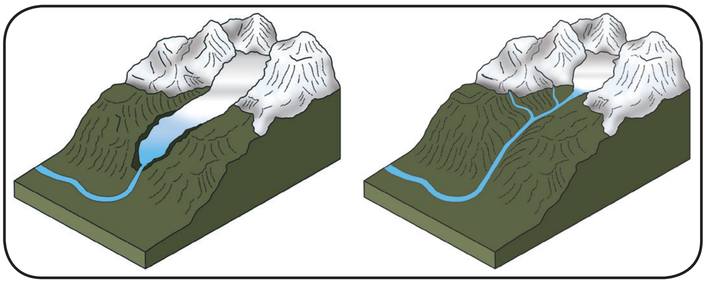


Figure 1a *Valley glacier* **Figure 1b** *Cirque glacier*

Approximately 10% of the earth's surface is covered by ice, that is an estimated 14.9 million sq. km, of which 4% is comprised of glaciers. A glacier is a large body of ice, built up over a considerable number of years, from accumulated and compressed snow. They can move, as their sheer mass allows them to 'flow'. There are 4 main glacier types mainly located within mountain ranges (see **Figures 1a-1d**).

Yet, whatever the size, location, or structure of the glacier, each operates as a **Physical System**. In this respect, all glaciers have:

- **Inputs** – that is water (as snow), as well as geological material e.g. rock eroded by the moving ice.
- **Stores, Flows and transfers** - the moving ice and material within, upon and underneath it, referred to as Moraine, is transferred but the glacier of ice which forms from the compacted snow is regarded as a store.
- **Outputs** - meltwater, calved icebergs and sediment deposited at the snout or glacial outwash material, water vapour (**Figure 2**).

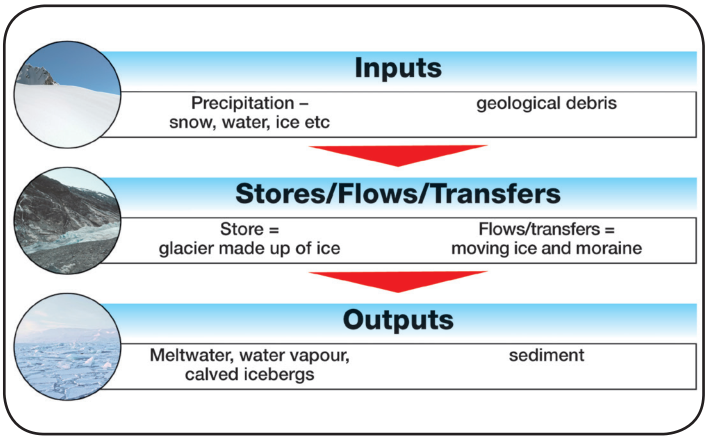


Figure 2 *The 'physical system' of glaciers*

What is mass balance or the glacial budget?

Using **Systems analysis** to investigate glaciers assists in our understanding of the mechanisms of glacial advance and retreat, as they either expand, shrink, or maintain an equilibrium. These structural changes are recognised as **Mass balance** (also known as the mass/glacial budget), which is the change in the mass of an ice body over time. The total mass alters because of the difference between 2 major processes:

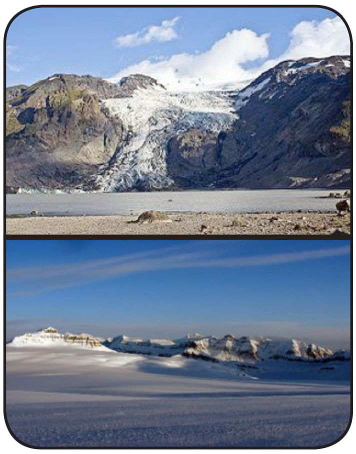


Figure 1c *Outlet glacier (top)*
Figure 1d *Icefield (bottom)*

Accumulation – all processes that add to the volume of the glacier i.e. snow (precipitated or windborne), and freezing rain, builds up in the accumulation zone, usually in the higher latitude regions of the glacier where there is more precipitation than loss due to melting, etc.

Ablation – all processes that reduce the volume of the glacier where snow and ice is lost due to melting, evaporation, and sublimation

Annual mass balance is the mass balance at the end of the year, calculated as the sum of the winter balance and summer balance. Accumulation and ablation usually show seasonal variation; the mass balance experiences an annual cycle of growth and depletion. If more snow accumulates in the winter on a glacier than snow and ice is lost during summer, the mass balance is **positive**. If summer melting exceeds the accumulation in the previous winter, the mass balance is **negative.** The seasonal distribution of precipitation is more important than the annual total amount. Mean summer temperature is the key to the dominant process in that season. This leads to considerable regional variation, e.g. at mid-latitudes it snows during the winter and melts during the summer, which is different from tropical regions, where ice melting and accumulation can occur at the same time.

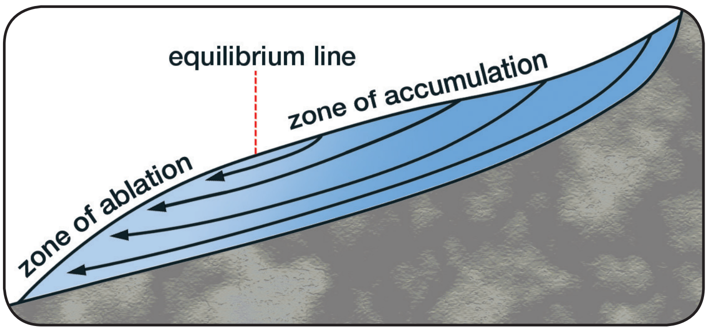


Figure 3 *The main zones where these processes occur*

By looking at the annual mass balance of a glacier over time, usually a decade, it is possible to calculate the **cumulative mass balance** to show trends. Cumulative balance is the overall impact of the totals of annual balance, and at present the trend is usually negative.

Measurement of mass balance has been used to interpret the variation in behaviour of glacial forms. Historically, it involved the use of topographic maps (still employed for comparative purposes or the establishment of base line of reference). Measurement methods include the following:

- One of the most straightforward ways to evaluate glacial change is to calculate the annual mass balance, using stakes and pits placed on the glacier (see **Figure 4**) and measuring their relative location seasonally.
- Aerial photography can be more efficient as it permits triangulation of snowline positions through repeated mapping. This has taken place on 50 glaciers of the Southern Alps in New Zealand for the last 3 decades (Such a sample size is essential as there can be significant variation in the response times of individual glaciers to climatic indicators).
- The thickness and volume of some of the largest glaciers can be monitored using Laser altimetry and global positioning satellite technology.
- Glacial length can be recorded as a dynamic indicator on a regular basis. It is easy to observe and measure, determining the location of the glacial snout.

The earliest mass-balance measurements were carried out on the Rhône Glacier in the Swiss Alps in the late 19th to early 20th century, but it was not until the 1940s that there was more comprehensive glacial surveying. After World War II, direct measurements were undertaken using methods seen in the diagram. The longest continuous time series of mass-balance data collected post World War II is from Storglaciären, Sweden, (Holmlund et al., 1996 and other dates – see resource listed).

Any change in mass balance is likely to occur gradually over time, with its associated alteration in glacial thickness, volume and, through differential flow patterns (e.g. basal sliding), its length. This latter indicator is a delayed one, but is easy to assess, whereas the thickness of ice is not delayed but is more difficult to gauge precisely (according to Haeberli, 1998).

Glacial mass balance over time

Glacial mass balances can be studied over a variety of **time scales**.

Longer term glacial/interglacial cycles over millions of years are usually explained by Milankovitch cycles based on orbital/astronomic forcing.

Shorter term both glacial and interglacial periods have fluctuations within them known as stadials (colder periods) and interstadials (warmer periods). The Little Ice Age and the Mediaeval warm periods are examples of historic changes. As well as the Milankovitch cycles a number of factors have been cited for these shorter term fluctuations such as Solar Forcing caused by variation in sunspot activity.

For both of these changes in mass balance feedback mechanism are seen as the key influence in the triggering of the fluctuations, for example, changes in the thermohaline circulation which has an influence on the temperature of the ocean currents.

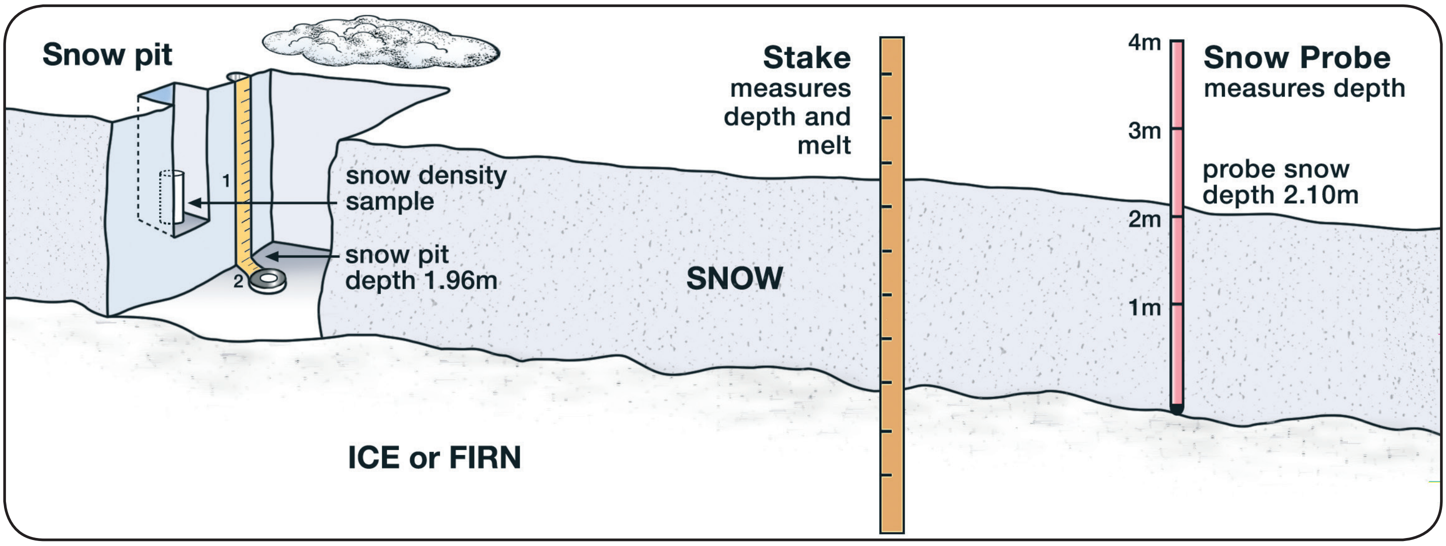
Present Day Changes

A global snapshot of the world's glaciers in 2015 shows the impact of climate warming. As the case studies show, some of the world's glaciers are still advancing, but the vast majority are retreating.

Scary Facts

- On the eastern slopes of the Rocky Mountains, the glaciers have lost 25-75% of their mass since 1850.
- In 1949 in Tajikistan in Central Asia, glaciers covered 18,500km² of land compared to 11,000km² in 2012 (a 38% decrease in the area covered by ice)
- 95% of Himalayan glaciers are in rapid retreat, for example, the Khumba Glacier (one of the highest in the world at the base of Everest) has retreated over 5km since 1953.
- Areas in Peru and Bolivia covered by glaciers shrunk 25% over the last 30 years.
- There are very few areas where glaciers are expanding – an example is that of the maritime glaciers in Scandinavia and here the elements of changing precipitation can contribute to a more positive mass balance.
- Data from satellite surveys of the Greenland Ice Sheet shows a huge decrease in the ice covered area and new data from West Antarctica shows it is beginning to follow trends in East Antarctica with a massive loss in shelf ice.

Figure 4 *Calculating the annual mass balance*



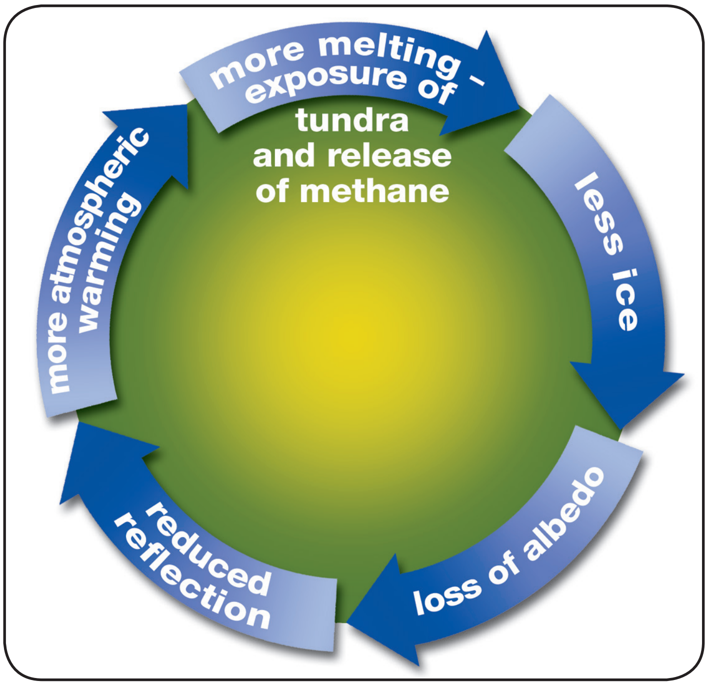


Figure 5 *Accumulation and ablation cycle*

Recent and regular surveys confirm this 'melt and retreat' is happening at an ever-increasing rate (exponentially). **Positive feedback** is amplifying the process of accumulation and ablation (**Figure 5**).

The destabilising effect of climate warming can also be looked at in two very significant contexts – changes to the hydrological cycle and changes in sea level as well as the actual changes in mass balance.

Causes of present day changes

Glacial response to changes in climate variables is not a simple relationship. Air temperature is particularly crucial as are both insolation and precipitation type and amount. Climate warming is impacting on these climate variables. There is an interplay between global, regional and local variations of temperatures and precipitation.

Clearly latitude is a fundamental control - for example, it has been shown that in the Himalayas, which is affected by a monsoonal climate, most glacial accumulation and ablation is in the summer months (Ageta and Fujita 1996, Fujita and Ageta 2000) but cold glaciers of polar regions can receive accumulation in any season (Chinn 1985, http://www.grid.unep.ch/glaciers/pdfs/2.pdf).

Therefore, as you will see in the case studies, in addition to latitude and solar variability, which impacts on isolation, other factors influencing glacial growth or retreat are really significant:

Factors influencing glacial growth or retreat

- Altitude – distribution of the area of glacier related to its elevation
- Chemical composition of the atmosphere
- Volcanic eruptions
- Impacts of meteorites
- Anthropogenic impacts
- Lakes – (proglacial) the glaciers end in deep water bodies which cause more melting and calving,
- Slope and local topography
- Debris cover – glaciers with heavy debris-cover have reduced melting and strongly limited 'retreat'
- Wind

Case studies of Current Glacial Mass balances

1. In the USA

The US Environmental Protection agency estimates that 'on average, glaciers worldwide have been losing mass since at least the 1970s. A longer measurement record from a smaller number of glaciers suggests that they have been shrinking since the 1940s. The rate at which glaciers are losing mass appears to have accelerated over roughly the last decade.' (report updated August 2016) Three US specific glaciers (see **Figure 6**) have shown an overall, cumulative decline in mass balance since the mid-1900s and more recently that decline has speeded up.

Annual trends vary, with some glaciers even gaining mass in certain years (for example, Wolverine Glacier during the 1980s), but the underlying trend is of a loss of glacier mass over time. As suggested earlier there is no one stable time series or spatial pattern but a highly variable trend series with marked contrasts even between glaciers that are in close proximity to each other. The three US glaciers are part of the **USGS Benchmark Glacier Survey**

Glacier National Park in **Montana** is indicative of these reported glaciological phenomena. Recently computer modelling has suggested that the park will be glacier free by 2030, if present rates of degradation continue. In 1850 there were 150 glaciers recorded within the park area but by 2010 according to USGS there were only 25 remaining including those that are very small in volume. These glaciers had grown from around 1400 AD with the start of the little ice age and were at their maximum volume circa 1850. Their greatest extent is deduced from the position of terminal and lateral moraines deposited prior to retreat. Dr Dan Fagre who has led a team surveying the glacial changes, concludes that they are currently melting due to natural climate change but that the rate of change has accelerated due to human influences. Some winters may experience cold 'snaps' of well below freezing temperatures but the long term mean temperatures are increasing. An increase of mean annual temperature since 1900 of 1.33 degrees has been recorded. Also, the main form of precipitation in recent years has been rain, so the snowpack is not accumulating.

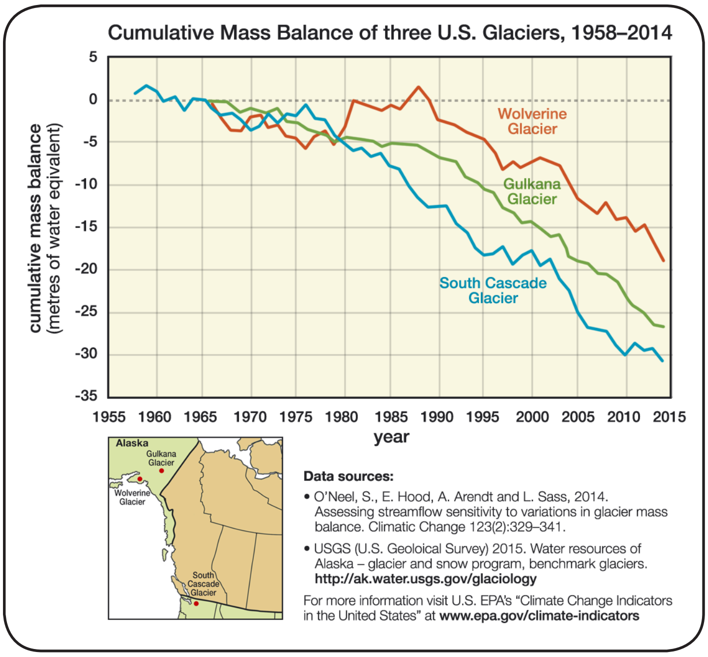


Figure 6 *The decline in three US glaciers*

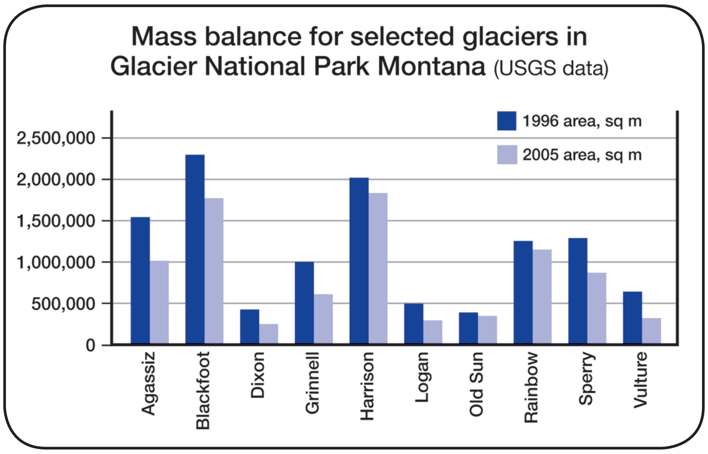


Figure 7 *Glacial National Park - Glacier area summary. Area data determined by aerial photo analysis USGS in conjunction with Portland State University*

Of the Park's remaining glaciers perhaps the most famous is the Grinnell glacier, partially because of its accessibility and also because Vice president Al Gore was photographed upon it when drawing attention to the perils of manmade climate change in 1997.The graph shows the extent of Grinnell's retreat compared to some of the other glaciers. Photos can be seen in many of the links cited at the end of the factsheet.

A series of dramatic paired photos illustrate the rate of retreat in many of the Park's glaciers: http://www.dailymail.co.uk/sciencetech/article-2239189/The-Glacier-National-Park-soon-change-global-warming.html

2. In the Himalayas

The Himalayas have an area of glaciers which covers 33,000 sq. km but **i**n 2008 it was noted that Himalayan glaciers were retreating at a rate of 10 -60 metres per annum. Many smaller glaciers of an area less than 0.2 sq. km have already disappeared. All valley glaciers in the area have receded by an average of 1 km since the Little Ice Age. This is attributed to global warming as with the Montanan glaciers. The IPCC states in its 3rd assessment report that the rate and duration of warming is greater than at any time in the last 100 years, but there have been estimates of rise of a greater magnitude in India, perhaps 3.3 degrees plus and even higher on the Tibetan Plateau. Whilst such statements may seem extreme, the underlying pattern is clear. During the 20th century the annual temperature in India rose by 0.05 degrees Celsius in each decade but more recently that average temperature is now 0.22 degrees. In the N W Himalayas, this has led to an overall rise of 1.6 degrees accompanied by a decreasing trend in winter snowfall. As has been stated warmer summer temperatures and decreased snowfall means a negative mass balance so the glacier diminishes - there is greater ablation than accumulation.

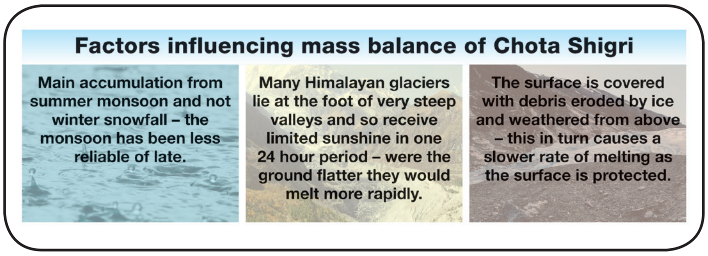


Figure 8 *Factors influencing mass balance of Chota Shigri*

With such mean temperatures, up to a quarter of the Himalayan glacial mass could disappear by 2050, but retreat is discontinuous, as the theory referred to earlier would suggest. Around 1970 there were some advances recorded in the Central Asian Himalayans.

Chota Shigri is a benchmark glacier in the Indian Himalayas lying in the Chandra river Basin about which a report was published in 2012 by the Indian Institute of Technology in Mumbai (see Figure 8) They concluded using satellite images from various sensors and topographic maps, that the glacier has recessed by 950 meters between 1962 and 2008 and has shown a negative mass balance for the 20 years preceding the study. A research project by Kumar and Dobhal covering 1962 – 1989 found that 1987 was the only year in which the glacier advanced. The average annual rate of retreat from1999-2008 was 15 meters. This generally means less rapid melting occurs and is one of the reasons cited for the lack of retreat of glaciers in the Karakoram region of Pakistan.

The combined effect of these variables however has not prevented retreat as the earlier figures indicated and studies show that the mass of the glacier has lost 20 feet across its surface. An ongoing study reported in the New Yorker magazine (April 2016) using ablation stakes, GPS technology and ground penetrating radar (to map the base of the glacier) notes that the thickness had decreased by 30 feet between 2009 and 2013 . The researchers also observed that one of the glaciers main tributaries seemed to becoming detached from the main flow probably as a result of thinning in the parent glacier.

3. The fluctuation of glaciers in South Island, New Zealand

A detailed piece of fieldwork and research work has been carried out on 50 index glaciers in the Southern Alps in New Zealand (www.niwa.co.nz). Each year NIWA scientists have used aerial photography to measure the end of summer snow line for 50 index glaciers, to estimate annual glacier mass balance, for most years over the past three decades. These surveys were sometimes augmented by fieldwork using stakes to measure mass changes in selected glaciers.

It was found that individual glaciers' response times to changes in climate varied considerably, from 5 to 10 years. Most of the steep alpine glaciers such as Fox and Franz Josef respond rapidly whereas large, low gradient, debris covered glaciers such as Tasman may take decades to respond.

The most recent maximum extent of glaciers was during the Little Ice Age (LIA) between the 17th and 19th centuries.

- Phase 1 – between 1910 and the 1970s there was some warming with massive wastage shown on historic photographs especially since the 1950s.
- Phase 2 – in 1977 the second phase started (at the end of the research project)

Despite continued regional warming, the recent period has been one of alternative gains and losses, resulting in near zero ice mass change overall in many Southern Alps glaciers, especially in the shorter fast response glaciers, which are now the same size as they were in 1977. On the other hand, the larger debris-mantled glaciers, which took time to adjust to the earlier post-1910 warming phase, actually kept their areas as measured after the Little Ice Age (LIA) for all but the last couple of decades, as they were well insulated by mantles of rocky moraine.

The surveys show that there are a number of factors which make the situation far more complex than 'global warming causes retreating glaciers' for numerous reasons:

- The slight regional warming on South Island, New Zealand has been paired with a more westerly atmospheric circulation over New Zealand, which has led to increased snowfall in the mountains just enough to overcome the impact of temperature increase, thus allowing glaciers such as Franz Josef and Fox to gain mass, so they rapidly pass their ice gains down to their snouts.
- For the larger glaciers, glacial lakes have begun to form at their snouts. Once a lake is formed, such as Lake Murchison, it eats at the glacier far faster than surface melt, as the ice cliff at the front of the glacier calves icebergs into the lake. This **positive feedback** ensures a rapid and catastrophic depletion of the glacier volume, almost like creating a **tipping point** for the glacier. So for some larger glaciers associated with proglacial lakes their volume decreased more than 10% over the last 30 years (with 92% of this coming from just 12 of the larger glaciers including Murchison and Tasman). For these glaciers only a small rise in ice volume is due to annual climate mass balance changes. Once a glacier has retreated away from its lake a state of equilibrium occurs and the dramatic losses in ice volume from calving are halted.
- This research from NIWA emphasises the complex nature of glacier response to climate change.

Activity

Reread the three case studies. For each, identify the most important factors which are driving the changes in mass balance.

Conclusion

The application of mass balance as a statistical analytical tool of glacial behaviour and environmental response is very valuable. As technology becomes more sophisticated and measurement more precise and reliable the evidence of the impact of climatic change upon glaciers can be more clearly assessed in this manner. Most evidence indicates that the world's glaciers are in the majority shrinking, though there is considerable variation in temporal and regional patterns. Even if the rate of global warming was to slow as a result of actions, such as the Paris Accord, it may be many years before the response will become apparent in glacial mass balances.

Further Reading

There is a wealth of visual material on present day glacier mass balance change. The list below is just a short sample.

- 'Glacier response to climate change' Jim Salinger, Trevor Chinn, Andrew Willsman, and Blair Fitzharris explain how fluctuations in New Zealand glaciers reflect regional climate change. Water & Atmosphere 16(3) 2008
- https://www.usgs.gov/media/images/glacier-animation/benchmarksurveys
- Global Glacier Changes: facts and figures UNEP and WGMS websites
- https://www.epa.gov/climate-indicators/climate-change-indicators-glaciers
- http://www.washingtonpost.com/sf/national/2015/11/26/ice-worlds/?utm_term=.1686b5e640b5
- http://www.serb.gov.in/pdfs/Publications/Chhota-Shigrii.pdf
- http://www.thehindu.com/opinion/op-ed/comment-melting-glaciers-changingclimate/article6542024.ece 11.
- http://www.newyorker.com/magazine/2016/04/04/investigating-chhota-shigri-glacier

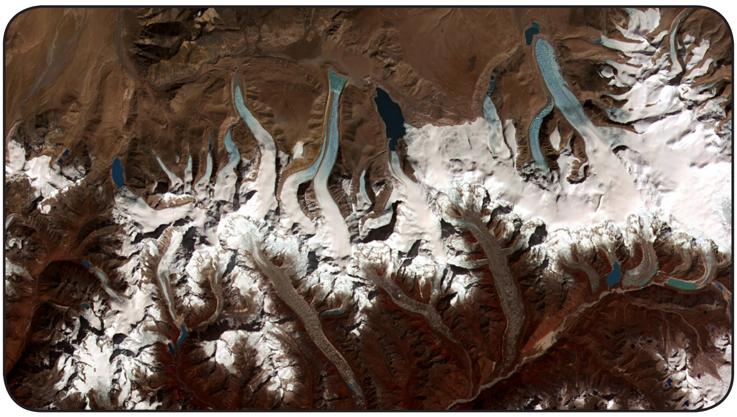


Figure 9 *Glacial lakes at the termini of receding glaciers (Bhutan-Himalaya)*

***Acknowledgements**: This **Geo Factsheet** was researched and written by **Sue Chamberlain**, a geography teacher in Hampshire, and published in **September 2017** by **Curriculum Press**.*
ISSN 1351-5136