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ENCYCLOPEDIA *of* SNOW, ICE AND GLACIERS

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"sediment gravity flow" was introduced to describe the major flow types involved in resedimentation processes and was defined as the flow of sediments or sediment–fluid mixture in which the interstitial fluid is driven by the grains moving under the action of gravity. Instability of the earlier sediments is the prerequisite for generation of flows involved in resedimentation processes. Such instability normally comes into existence either due to oversteepening of the parent deposit or through some process of liquidization including seismogenic slumping and storm wave-induced landslide.

RETREAT/ADVANCE OF GLACIERS

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Definition

The retreat and advance of glaciers traditionally refers to changes in the position of a glacier terminus over time. More recently, quantification of the retreat/advance of glaciers has been extended to include measurement of ice thickness changes, which provides a more direct picture of how ice volume is changing as it is directly related to mass balance. These measures are the most common way in which the response of glaciers to climate change is monitored, as conditions favorable for positive glacier mass balance (e.g., increasing snowfall, lower temperatures) typically result in glacier advance, while negative mass balance conditions (e.g., lower snowfall, higher temperatures) typically result in glacier retreat (Figure 1).

Controls on glacier terminus advance/retreat patterns

The position of a glacier terminus is primarily defined by the balance between two factors: ice motion that is driving the ice front forward, and melt/calving that results in loss of the ice front. Changes in either, or both, of these factors control the ultimate terminus position. For example, the terminus of a glacier will retreat if surface melt is greater than the rate of forward ice motion, even if there is still substantial ice flow along the lower glacier. In another example, a glacier will advance if surface melt rate stays constant but ice velocity increases.

The initial reaction time of a change in terminus position to a climate perturbation can be asymmetric as an increase in air temperature can lead to a rapid retreat via immediate melting at the terminus, whereas an increase in snowfall can take years or longer to produce a terminus change due to the time it takes for ice to flow from the top to bottom of a glacier. The reaction time differs from the response time, which is defined as the time it takes for a glacier to completely adjust to a climate perturbation (Haeberli and Hoelzle, 1995). The response time and total change in terminus position for a given climate forcing depends to a large extent on the original size of the glacier, with larger glaciers experiencing larger terminus changes due to the requirement for mass conservation (Nye, 1965; Johannesson et al., 1989). When combined with models of ice dynamics, this enables reconstruction of past mass balances from glacier length changes (e.g., Hoelzle et al., 2003) and the prediction of future glacier advance/retreat patterns for given climate forcings (Oerlemans et al., 1998). The change in terminus position for the same external forcing will also vary between glaciers depending on the geometry of the valley in which they lie. Glaciers which have a large, broad accumulation area that feeds into a narrow valley will undergo large changes in terminus position in response to changes in mass balance. Conversely, ice masses that have broad ablation areas (e.g., ice caps) would see much less variation in terminus position for the same change in mass balance.

Given the above considerations, the relationship between the retreat/advance of glacier termini and climate is rarely straightforward. Glaciers are always adjusting to their surrounding conditions, since weather and climate can and do vary on much shorter timescales than glaciers. Glacier terminus changes typically reflect a low-frequency response to external forcing (UNEP, 2007), with short-term climate variations being averaged out over timescales of a few years to decades for glaciers in wet, maritime climates where there is high mass turnover and relatively fast flow (e.g., New Zealand Alps, Patagonia, Alaska; Paterson, 1994; Raper and Braithwaite, 2009). In contrast, glaciers in drier, more continental climates (e.g., Arctic Canada) have a lower mass turnover and flow relatively slowly, which means that it can take them decades to centuries or longer to respond to changes in climate.

As techniques for monitoring glaciers have developed (e.g., airborne laser altimetry; Hopkinson and Demuth, 2006), it is clear that measurement of the position of a glacier terminus over time provides an imperfect measure of how the glacier is responding to external factors such as climate. Measurements of changes in ice thickness provide a more direct measure of these effects, as the response time of glacier surface height changes to external forcing is typically much shorter than the response time of changes in terminus position (UNEP, 2007). Increases in surface elevation typically mean that a glacier is healthy and gaining mass (e.g., due to increasing snowfall and/or reduced melt), while decreases in surface elevation typically indicate that a glacier has a negative mass balance and is wasting away. These techniques are discussed in more detail elsewhere in this volume (e.g., see under "*Glacier Mass Balance*").

Historical terminus advance/retreat patterns

Despite the limitations and uncertainties in interpreting the causes of changes in glacier terminus position, they are

Retreat/Advance of Glaciers, Figure 1 Photo illustrating retreat of the terminus position of the Easton Glacier, North Cascade Mountains, USA, between 1985 and 2003. (Source and copyright: http://en.wikipedia.org/wiki/File:Eastonterm.jpg).

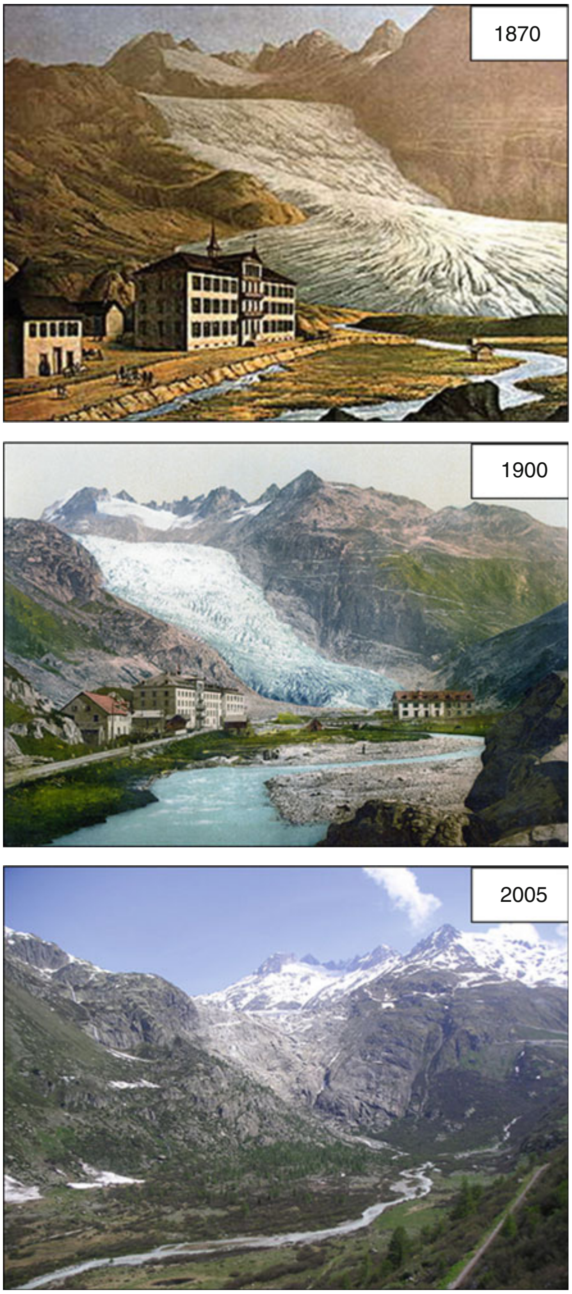
still one of the most widely used measures of glacier health. This is because glacier terminus position is one of the most visible and easily measured glaciological indicators, both in historical sources (e.g., paintings, photography) and modern satellite imagery. For example, the longest known record of changes in glacier length is provided by the Untere Grindelwaldgletscher, Switzerland (Oerlemans, 2005), whose cumulative length changes have been reconstructed since 1534 (Zumbühl, 1980). Over long time periods, air temperature provides the dominant control on terminus position as it provides the main control on glaciologically important climate parameters such as the long-wave radiation balance, the ratio of solid to liquid precipitation, and turbulent heat exchange (WGMS, 2008).

It can be problematic to connect climate changes to the advance/retreat pattern of a single glacier, but consistent changes across many glaciers in the same region increases confidence that air temperature is providing a dominant control. For example, widespread advance of glaciers in the European Alps during the Little Ice Age between ~1650 and 1850 occurred as a response to cooler conditions during this time (Grove, 1988). Since then, there has been widespread glacier retreat in this region as a response to climate warming. For example, the terminus of the Rhonegletscher has retreated dramatically between 1870 and the present day (Figure 2). Useful comparisons of glacier changes over time are available at http://www.swisseduc.ch/glaciers/index-en.html.

Complicating controls on terminus advance/retreat patterns

Interpretation of the terminus retreat/advance pattern of glaciers as an indicator of climate change can be complicated in situations where morphological and internal processes provide a strong control on glacier changes. In particular, there are three types of glaciers where this can be a factor (WGMS, 2008):

1. Surging glaciers: on these ice masses, dramatic changes in terminus position and surface height are mainly related to periodic redistribution of mass within the glacier due to changes in internal flow dynamics. For example, the terminus of the Kutiàh Glacier, Pakistan, advanced by 12 km over an approximately 3-month period in 1953 due to a surge (Desio, 1954). These changes are largely unrelated to external climate conditions, which means that surge-type glaciers are usually omitted from inventories that use glacier advance/retreat patterns to assess the impacts of climate change.
2. Tidewater glaciers: glaciers that end in freshwater or marine locations have floating termini, which can display complex terminus responses defined by relationships between factors such as water depth, pinning points, ice dynamics, tides, and climate forcing (Benn and Evans, 1998). Consequently, advance/retreat patterns of individual tidewater glaciers are often problematic to interpret in terms of climate forcing, particularly over short timescales. However, tidewater



Retreat/Advance of Glaciers, Figure 2 Retreat of Rhonegletscher, Switzerland, from the end of the Little Ice Age (1870) to the present day. (Source and copyright: http://de.wikipedia.org/wiki/Rhonegletscher).

glaciers can provide useful information on climate changes if they display consistent terminus advance/retreat patterns over large areas and for long periods (e.g., Joughin et al., 2008). The tidewater advance/retreat pattern is typically asymmetric, with advances occurring over long periods (centuries) and retreats occurring relatively rapidly (decades). Consequently, a majority of calving glaciers would be expected to be advancing in a constant climate.

3. Debris-covered glaciers: glaciers in tectonically active mountain ranges (e.g., Himalayas) are frequently heavily debris covered over their lower ablation areas, with debris thicknesses of >1 m common (Shroder et al., 2000). This debris is effective at protecting the ice from melting, which means that their terminus advance/retreat patterns are commonly muted compared to nearby non-debris covered glaciers (WGMS, 2008). Negative mass balance on these ice bodies often results in downwasting of the glacier in situ, rather than a distinct retreat of the terminus.

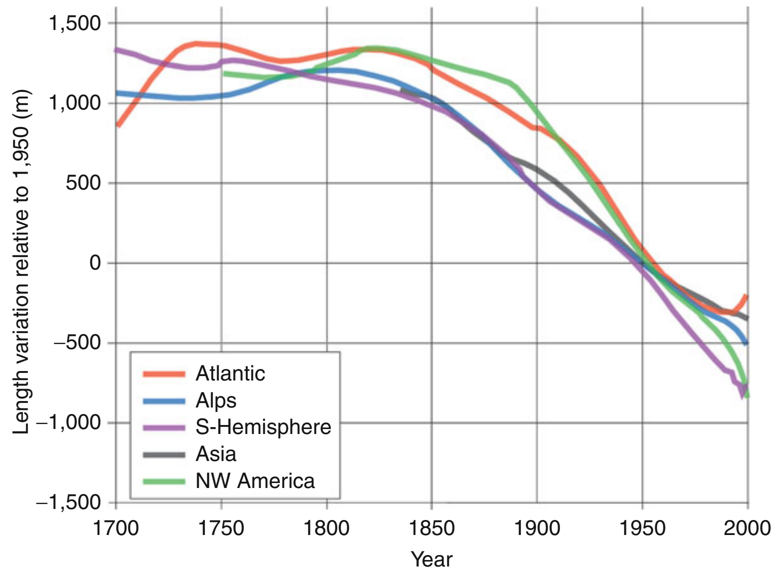
World glacier monitoring service

The World Glacier Monitoring Service (http://www.geo.unizh.ch/wgms/), based at the University of Zurich, Switzerland, maintains the main global database of the advance/retreat patterns of glaciers. Researchers from around the world are encouraged to provide standardized annual measurements of parameters such as glacier mass balance, volume, area, and length that are inventoried by WGMS. Since the late 1950s, they have published the "Fluctuations of Glaciers" series every 5 years that provides the main record of these parameters and how they are changing over time. This information is used by agencies such as the Intergovernmental Panel on Climate Change in the compilation of their reports on the impacts of climate change (e.g., IPCC, 2007). In addition, WGMS/UNEP also recently published the book on "Global Glacier Changes: Facts and Figures" that provides a valuable summary of glacier advance/retreat patterns around the world (WGMS, 2008).

The WGMS assesses the advance/retreat patterns of glaciers within a hierarchy of measures of glacier health under the auspices of the Global Terrestrial Network for Glaciers (http://www.geo.unizh.ch/wgms; Haeberli et al., 2000). Within this strategy, detailed monitoring of glacier mass balance and flow dynamics on an annual basis is limited to a relatively small number of sites ($\sim 10^1$–10^2) where access and logistical cost allows. These locations provide the most direct measure of glacier health, but are limited by their lack of spatial coverage. To expand on this coverage, monitoring of changes in glacier length is completed at a much larger number of glaciers ($\sim 10^2$–10^3) on a less regular basis (approx. every 5–10 years). This provides a global picture of how glaciers are changing over time, and monitoring over longer time periods increases confidence that changes in terminus position represent long-term trends rather than annual anomalies.

Recent advance/retreat patterns of glaciers and ice caps

One of the most comprehensive analyses of glacier terminus advance/retreat patterns is provided by Oerlemans (2005), who compiled mean length variations of 169 glaciers over the period 1700–2000 (Figure 3). The spatial



Retreat/Advance of Glaciers, Figure 3 Large-scale regional mean length variations of glacier tongues (Oerlemans, 2005). The raw data are all constrained to pass through zero in 1950. The curves shown are smoothed with the Stineman (1980) method . Glaciers are grouped into the following regional classes: SH (tropics, New Zealand, Patagonia), northwest North America (mainly Canadian Rockies), Atlantic (South Greenland, Iceland, Jan Mayen, Svalbard, Scandinavia), European Alps and Asia (Caucasus and central Asia). (Source: IPCC 2007, their Fig. 4.13). (Source and copyright: http://www.ipcc.ch/publications_and_data/publications_and_data_figures_and_tables.htm).

and temporal coverage of these records is incomplete due to the lack of continuous long-term monitoring of glaciers, but the changes are still remarkably similar from many different regions around the world. In the early period (1700–1850), glacier lengths were largely stable during the Little Ice Age, when mean temperatures were approximately 1.0°C cooler than at present (Oerlemans, 2005). Consistent retreat began around 1850 and has continued up to the present day, with glacier fronts on average ~2 km further back in 2000 than in 1850. In the European Alps, this has coincided with a loss of approximately two third of glacier volume between 1850 and the early 2000s (Zemp et al., 2006).

Glacier terminus retreats have accelerated since the early to mid-1980s in many parts of the world (Solomina et al., 2008; WGMS, 2008). In single very warm and dry summers, such as 2003, losses of up to 5–10% of the total remaining ice volume of the European Alps have been observed. This has lead to concerns that the remaining glaciers may almost entirely disappear within the next few decades (Zemp et al., 2006). Similar dramatic reductions have been recorded in North America, with widespread glacier area and volume losses in the Rocky Mountains (De Beer and Sharp, 2007; Demuth et al., 2008) and Alaska/Yukon (Arendt et al., 2002; Larsen et al., 2007), particularly at low elevations. Similar changes have also occurred in the Patagonia Icefields (which hold most of the ice in South America), with the majority of outlet glaciers dramatically retreating since the mid-1900s (Lopez et al., 2010), including a doubling of ice thinning rates over 1995–2000 compared to 1968/1975–2000 (Rignot et al., 2003).

Many high-altitude tropical glaciers in locations such as New Guinea and Africa have completely disappeared during the latter part of the twentieth century (Cullen et al., 2006; Klein and Kincaid, 2008), with a poor outlook for the remaining ice bodies in these areas (WGMS, 2008).

While most glaciers and ice caps have undergone widespread retreat over the past century, there are a few areas where glacier advances have been observed. In particular, glaciers on the west coast of New Zealand and Norway showed marked advances between the early 1980s and 2000 (WGMS, 2008). These areas are climatologically similar, being dominated by westerly atmospheric circulation across open ocean that produces very high precipitation amounts (>10,000 mm yr^{-1} in some parts of New Zealand). Their recent advances have been linked to increases in the strength of this circulation, with an increase in El Niño/Southern Oscillation (ENSO) events corresponding to increased precipitation in New Zealand, and a strongly positive North Atlantic Oscillation (NAO) corresponding to increased precipitation and a seasonal shift to more winter precipitation in Norway (Chinn et al., 2005). Recent glacier advances and velocity increases have also been reported for the Karakoram Himalaya, again as a response to increases in precipitation (Hewitt, 2005; Quincey et al., 2009).

To put these recent changes in context, it is also useful to consider the changes in glacier extent that have occurred since the end of the last glacial period. At the peak of the last glaciation (21 ka), ice covered approximately one third of the land surface on Earth (Paterson, 1994), with most of North America and Northern Europe covered by the Laurentide and Eurasian Ice Sheets, respectively. Available field evidence indicates that warming during the Early Holocene caused dramatic glacier retreats in most mountainous areas such as the Alps, with glaciers reaching similar extents ~11–10 ka as those at the end of the twentieth century (WGMS, 2008). These retreats were punctuated by temporary readvances, such as one at 8.2 ka that appears to be related to changes in thermohaline circulation of the oceans (Alley and Agustsdottir, 2005). However, glaciers in most parts of the world continued their general retreat and reached their minimum extents ~4–6 ka (Solomina et al., 2008). Minor advances and retreats have occurred since then, with the most recent glacier advances occurring during the Little Ice Age that ended around 1850.

The above examples highlight the complexity of glacier responses to climate change over different time periods. The vast majority of glaciers and ice caps around the world have undergone dramatic retreat since the end of the Little Ice Age, but these patterns have been occasionally punctuated by local advances, particularly in response to increases in precipitation. These local increases appear to be largely temporary in nature, however, and are insufficient to counteract the dramatic losses that have occurred elsewhere. Glacier retreat patterns during most of the Holocene appear to be largely driven by natural changes in incoming solar radiation caused by changes in the Earth's orbit (Solomina et al., 2008). In contrast, glacier length changes in the past couple of decades have occurred at rates that cannot be explained by natural variability, making it highly likely that human-induced forcing (e.g., due to increased atmospheric CO_2 levels) is the primary cause (IPCC, 2007).

Summary

In summary, advance/retreat patterns of glacier termini provide one of the most easily measured and recognizable indicators of climate change. Advancing glaciers typically indicate positive mass balance conditions and a healthy glacier, while terminus retreat is usually indicative of negative mass balance. There are many factors that can complicate interpretation of the causes of changes in terminus position, but in general similar advance or retreat patterns across many glaciers in the same region can be interpreted in terms of changes in climate. Air temperatures typically provide the primary control, although precipitation can also be important in some locations (e.g., maritime regions). Modern satellite imagery now enables the monitoring of glacier terminus positions over large areas, which has revolutionized understanding of the spatial patterns of recent changes.

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Cross-references

Climate Change and Glaciers
Dynamics of Glaciers
Glacier Hydrology
Glacier Mass Balance
Glacier Motion/Ice Velocity
Glacier Surging
Global Warming and its Effect on Snow/Ice/Glaciers
Sea-Level

RIME ICE

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The white, granular deposits of ice formed on cold surfaces by freezing of supercooled vapor or water droplets carried by the wind are known as rimed ice.

The rimed ice is formed on objects that are at a temperature below the freezing point. Rime occurs when supercooled water droplets (at a temperature lower than 0°C) come in contact with a surface that is also at a temperature below freezing. The droplets are so small that they freeze almost immediately upon contact with the object. Rime ice is commonly formed on windward upper slopes of mountains that are enveloped by supercooled clouds. These rime deposits generally take the form of long plumes of ice oriented into the direction of the wind. Rime is composed of small ice particles with air pockets between them and causes its typical white appearance and granular structure. Because of the rapid freezing of each individual supercooled droplet, there is relatively a poor cohesion between the neighboring ice particles, and the deposits may easily be shattered or removed from objects they form on. Rime ice can form on various surfaces like aircraft, glacier surface, trees, grass, etc.

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RIVER ICE HYDROLOGY

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Definition

Hydro-meteorological effects on river ice evolution and its effect on river hydrology.

Introduction

In cold and temperate regions of the world, wintertime operation of river systems is a key element in the management of surface water resources. River ice is known to affect many of the world's largest rivers. In the Northern Hemisphere, about 60% of rivers experience significant seasonal effects of river ice (Prowse, 2005). The formation and evolution of river ice is affected by the river discharge supplied by the catchment. The hydrological effect of river ice is mainly its influence on the river discharge and stages. In addition to ice-induced extreme flow events, river ice can also have serious environmental and ecological effects (e.g., Prowse, 2001a, 2001b). In the last couple of decades, significant progress has been made on river ice research. Several books and reviews on river ice processes and the state of research have been published (Ashton, 1986; Beltaos, 1995, 2008a; Beltaos and Prowse, 2009; Donchenko, 1987; Gerard, 1990; Prowse, 2005; Shen, 2003, 2006). An overview of river ice processes and its hydrological effects will be presented.