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SPOT IMAGE

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SATELLITES MONITORING MOUNTAIN GLACIERS

Glaciers provide some of the most spectacular evidence of recent climate change. But paradoxically, they have not been studied a lot because they are in remote locations scattered across the globe. Today, glaciologists are using optical satellite imagery combined with innovative processing techniques to reveal alarming recent trends.

Harbingers and agents of global warming

The rapid retreat of mountain glaciers makes them an important factor in and a telltale indicator of climate change. Although the total surface area of all these glaciers—excluding the Greenland and Antarctic ice sheets—covers barely more than the area of France (approx. 680,000 sq.km.), they are melting so fast that in the last 10 years they have contributed one-third (approx. 1 mm/year) to the total rise in the global mean sea level of 3 mm/year. Locally, glaciers regulate river flow by storing water as ice during the wet season and releasing it during the dry season. They thus sustain river levels and are vital in preserving the supply of water—for crop irrigation, electric micro-power stations and drinking—to mountain populations. But can they continue fulfilling this role in the future? The health of mountain glaciers, which are found at a range of altitudes and all latitudes, is also an excellent indicator of climate fluctuations. Glaciers reveal variations in temperature and precipitation in regions where weather measurements are scarce and uneven. These are some of the many reasons why we should keep a close eye on these harbingers and agents of global warming.

Our knowledge of glacier mechanisms and evolution remains sketchy and limited by a lack of observation data. The harsh conditions of high mountain ranges—where snowstorms and biting cold combine with the risks posed by crevasses and avalanches—make acquiring in-situ measurements especially difficult. Consequently, of the 160,000 glaciers dotted around the globe, only 50 of the smallest and most easily accessible are regularly inspected by glaciologists in the field. Satellite imagery obviously would seem an effective solution for observing glaciers globally and studying the largest specimens. But satellite-based remote sensing of glaciers is complicated by their hugely varying size—ranging from a few hundred square metres to thousands of square kilometres—and to the topography of mountain areas. Further, glacier surfaces can change in the space of a few days as a result of snowfall or melting. As a result, it is often difficult to establish coherence or correlations when comparing two satellite images.

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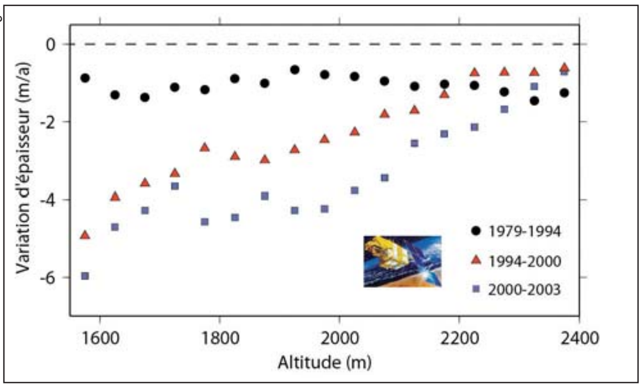
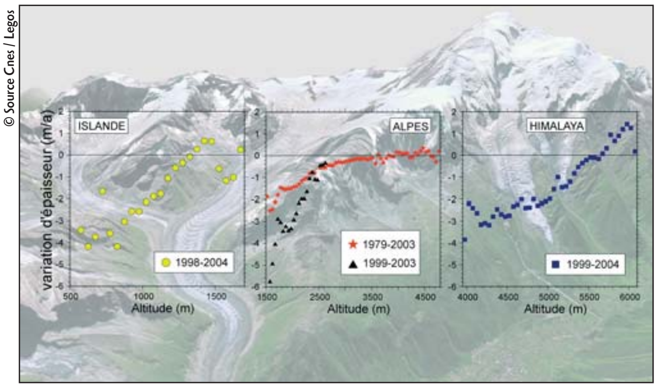


Variation in thickness of the Mer de Glace, French Alps. Thinning from 1979-1994 is fairly constant at all altitudes, but from 1994-2000 and 2000-2003 ice loss accelerated chiefly in the ablation zone, nearest the glacier's ice tongue.



Variation in thickness (in metres per year) of the Icelandic, Alpine and Himalayan glaciers. All exhibit significant thinning at low altitude and limited thinning in accumulation zones at high altitude.

>>> Lastly, glaciers covered in snow or ice have a high albedo and therefore reflect most radiation back into space, saturating imagery unless instrument gains have been pre-adjusted. So, there are many obstacles but they can be overcome through careful definition of geometric and radiometric imaging parameters and by post-processing to adjust for conditions in high mountain ranges.

Today, high-resolution optical imagery, notably from the SPOT 5 satellite, allows us to measure two key glacier variables: their rate of surface flow and variations in volume. The Mont-Blanc massif in France is an excellent site for evaluating these innovative methodologies against field survey data collected by the LGGE glaciology laboratory in Grenoble. By comparing with ground truth, methods can be validated and applied to more remote regions like the Icelandic ice sheets, the glaciers of the Indian Himalayas or the polar regions.

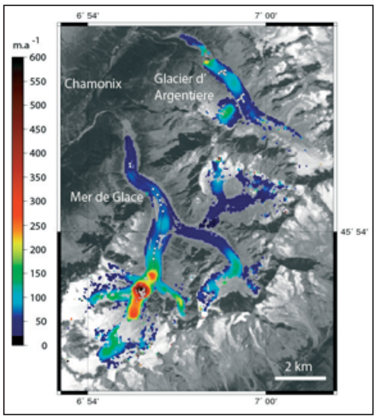
Measuring ice volume variations and glacier dynamics from space

One key parameter is ice volume variation. Precise topographies derived from SPOT stereopair images for different years are compared to estimate variations in ice thickness. First, rocky and stable areas around glaciers in digital elevation models (DEMs) are adjusted. We then compare our measurements obtained in the Mont-Blanc massif for the periods 1979-1994, 1994-2000 and 2000-2003 with in-situ readings, indicating an accuracy of ± 1-2 metres. Thinning of ice at low altitude has clearly accelerated in the last 10 years, whereas no significant trend emerges above 3,000 metres. For example, opposite Montenvers station at 1,600 metres, the Mer de Glace is losing 3-4 metres of ice every year and steps have to be provided for mountaineers and tourists to get off the cog-wheel train from Chamonix. We have seen that increased surface melting of this glacier, due to rising temperatures, only accounts for a little less than one-half of these large reductions in thickness. This is important to note, because it shows that the relationship between glacier variations and climate change is complex. We shall return to what is causing the other half of this glacial thinning later.

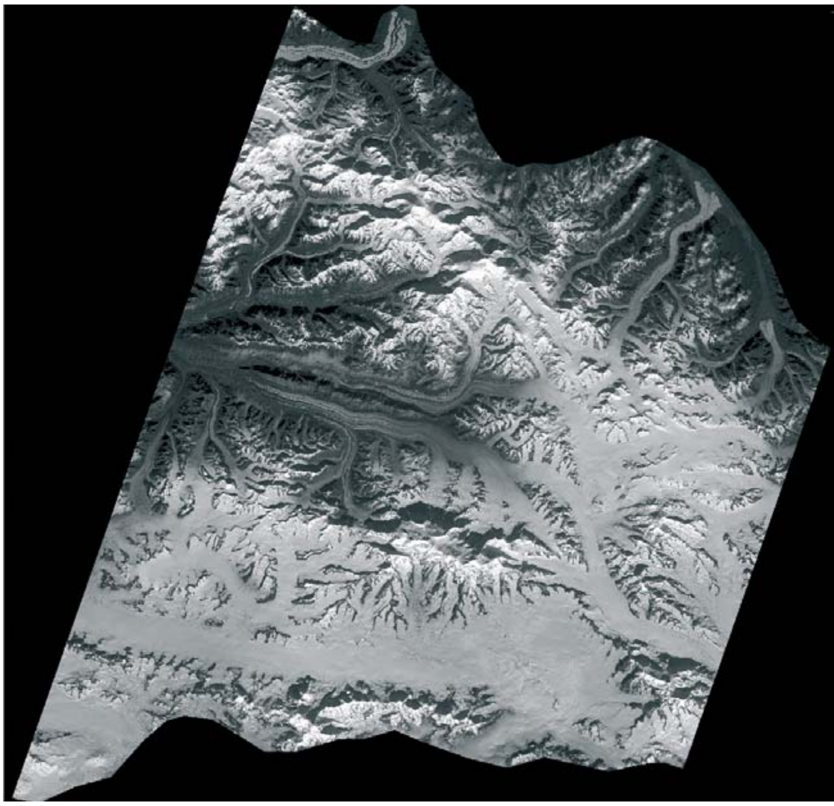
Comparing recent SPOT 5 DEMs (2004) with SRTM or airborne data also reveals significant thinning at low altitude in Himalayan and Icelandic glaciers over the last five to six years. Similar losses of ice mass in the Alps, Iceland and the Himalayas are surprising given their very different climates. The negative mass balances of these three regions suggest they are making a significant contribution—more than 0.1 mm/year—to rising mean sea level.

Another important parameter in describing a glacier's health is its flow. In mountain glaciers, flow determines the down-glacier redistribution of mass accumulated at high altitude. In polar ice caps, the rate at which ice flows outward into the ocean through calving of icebergs directly controls their mass balance. An all-weather technique known as radar interferometry can be used to measure this type of flow by identifying phase differences in radar images. But this technique is highly sensitive to changes in the glacier's surface and cannot currently be applied routinely for mountain glaciers. We therefore turned to another method based on correlating optical images. This is achieved by overlaying high-resolution images acquired several weeks apart, then correlating them to highlight ice movement. Comparisons with in-situ measurements of glacial movement indicate this method is accurate to ± 50 cm (one-fifth of a pixel) for displacements derived from SPOT 5 images of the Mont-Blanc massif. Comparing recent satellite measurements with readings taken by LGGE from 1965 to 1980 reveals that the tongue of the Mer de Glace has slowed by 30 to 40 percent. So we now have our explanation for the rest of this glacier's thinning. A simple model shows that this deceleration could account for nearly half of the thinning of the Mer de Glace at altitudes below 2,200 metres, which confirms how vital it is to monitor glacial dynamics closely.

We used the same SPOT 5 image correlation technique to study the dynamics of Iceland's Vatnajökull ice field. This time, we wanted to measure vertical movements rather than horizontal flow. We therefore correlated SPOT 5 images acquired at very similar oblique viewing angles to detect uplifting of an ice platform floating on the Grímsvötn subglacial lake at the heart of Vatnajökull. By mapping this uplifting, we are establishing the extent of the sub-



Ice flow rate (in metres per year) of glaciers in the Mont Blanc massif, against a SPOT 5 backdrop.



SPOT 5 HRS orthoimage of St. Elias Mountains, Alaska. The HRS Glaciology product, consisting of 3 HRS DEMs derived from different parameters and a control orthoimage, enables variations in ice thickness and flow rate of ice masses like the extensive mountain glaciers shown above to be calculated by comparison. Spot Image devised this product under a joint project with the French space agency CNES for International Polar Year.

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glacial lake and estimating geothermal activity in this zone at the foot of an active volcano. Icelandic ice fields will continue to be monitored in the years ahead, notably with the support of the Planet Action initiative (see *Spot Magazine* n° 42).

Building a global picture of glacier variations

Using high-resolution optical satellite imagery and processing techniques adapted to glacier environments, we can now characterize the regional-scale impact of climate change on glaciers. In the future, these same tools should help us to establish a global picture of changes in continental ice masses, particularly in the still unexplored polar regions. To this end, Jérôme Korona is leading a project in partnership with the French space agency CNES and Spot Image to build up an exceptional archive of SPOT 5 HRS imagery. SPOT 5's HRS instrument (High Resolution Stereoscopic) is able to acquire stereopairs at a resolution of around 10 metres with unmatched spatial coverage, thanks to its 120-kilometre swath width and its ability to image strips up to 600 kilometres long. IGN is also involved in this SPIRIT project (SPOT 5 stereoscopic survey of Polar Ice: Reference Images and Topographies) to derive a baseline topography that is so sorely lacking for scientists studying the polar ice sheets.

SPOT 5'S HRS INSTRUMENT SERVING GLACIOLOGISTS

CNES and Spot Image are currently building up a large archive of SPOT HRS imagery for the International Polar Year. An initial campaign in the Northern Hemisphere covered some 830,000 sq.km. of the polar regions. This project is funding production and distribution of DEMs to the international scientific community to support the study of changes in the polar ice sheets.
The Antarctic campaign now underway is pursuing the ambitious objective of covering two million sq.km. of the ice sheet in an effort to give scientists a clearer picture of our changing planet.

Taiwan's National Space Organization (NSPO) is also coming on board for the International Polar Year (IPY). In partnership with Planet Action, NSPO began this summer acquiring imagery with its new FORMOSAT-2 satellite, which combines high geometric resolution (2 metres in black-and-white) with excellent revisit times (about one useful image a week in cloudy mountain areas). This imagery will enable a detailed description of spatial and temporal variability of glacial flow rates, notably for large outlet glacier tongues in the polar ice sheets.
These FORMOSAT-2 images should also make it possible to monitor what's going on in Antarctica's subglacial lakes by observing the vertical movements of the overlying ice.
Remote sensing has become a vital tool for monitoring temperate and polar glaciers. Our work has been made possible by the recent advent of satellite imagery at resolutions on the order of a few metres. While very-high-resolution imagery—for example from the future Pleaides mission, offering submetric resolutions—will be useful for studying changes in smaller features like individual glaciers in closer detail, it usually implies much narrower spatial coverage, which is an obstacle when monitoring the biggest ice fields and ice sheets. For this reason, SPOT 5 with its HRG and especially its HRS instrument is currently the most attractive remote-sensing satellite for the glaciology community. Let's hope it still has many years of service left to go—if possible, until 2032, the date being mooted for the next IPY. ■

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PIERCING THE SECRETS OF THE JAKOBSHAVN ISBRAE GLACIER

The main front, or ice tongue, where icebergs calve from the glacier has retreated 40 kilometres since 1850. But this process has not been constant. From 1850 to 1964, the tongue retreated about 0.3 km a year, speeding up slightly in 1929-1930. The front remained somewhat constant from 1964 to 2001 and then accelerated significantly, reaching a speed of 3 km per year from 2001 onwards.

The ice tongue of the Jakobshavn glacier on Greenland's west coast has retreated significantly in the last five years. At the same time, it has thinned and started to flow faster. These changes have been confirmed in processed SPOT 5 HRS imagery.

Outlet glacier in Greenland

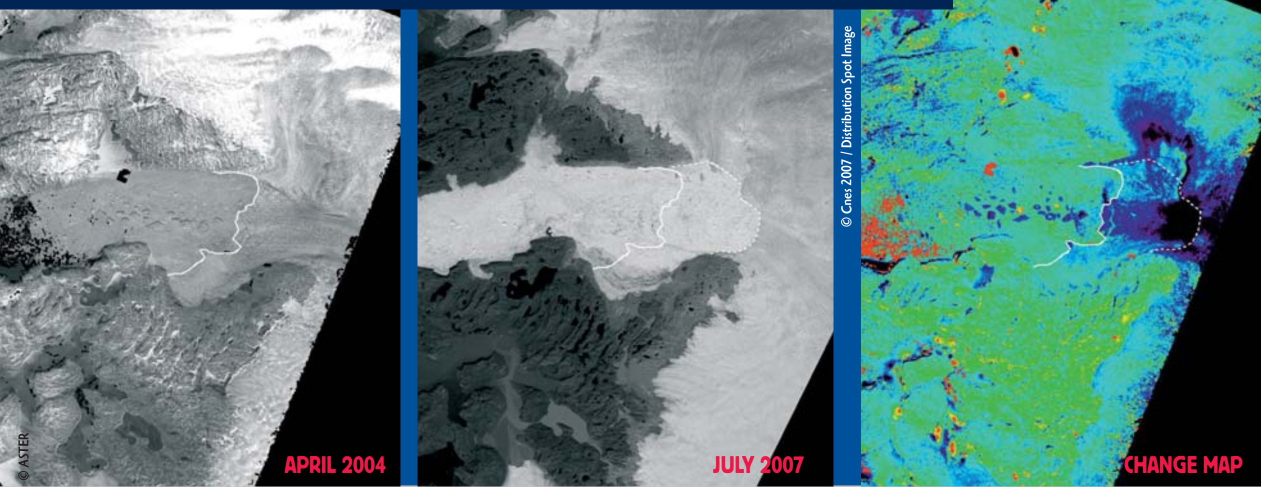
The town of Jakobshavn (Ilulíssat in Greenlandic) lies near the mouth of the eponymous fjord from where icebergs calve off the Jakobshavn Isbrae glacier into Disko Bay. A UNESCO world heritage site, this glacier is one of the largest on the Arctic ice sheet, discharging some 35 billion tonnes of ice into the sea every year, that is, 6 to 10 percent of the total mass of ice discharged into the Northern Hemisphere oceans. Jakobshavn Isbrae is now the world's fastest-flowing glacier and is estimated to be responsible for 4 percent (0.06 mm) of the recent rise in sea level across the globe.

Since 2004, new ASTER and Landsat satellite data have revealed a clear break in the glacier's advance. Its northern and southern sections are exhibiting different behaviour, with the ice streams driving the flow of ice to the calving front moving at different speeds. The rate of ice flow doubled between 1985 and 2006, from 17 metres to 35 metres per day.

Details in the DEM

SPOT 5's HRS instrument has been used to map the Jakobshavn glacier precisely in three dimensions. Comparing a digital elevation model (DEM) generated by IGN, France's survey and mapping agency, from SPOT 5 HRS imagery acquired in 2007 with a DEM from April 2003, the LEGOS space geophysics and oceanography research laboratory found that the glacier had thinned rapidly. The glacier's speed was also measured by comparing two HRS orthoimages acquired 10 days apart. The main ice stream peaked at 42.5 metres per day (15.5 kilometres per year), making Jakobshavn Isbrae well and truly the world's fastest glacier. ■

HRS GLACIOLOGY: A NEW TOOL FOR DETECTING ICE THICKNESS VARIATIONS



This change-detection map was generated by correlating a DEM from April 2004 with a SPOT 5 HRS DEM from July 2007.
The map clearly shows thinning at the glacier's calving front and further upfield.