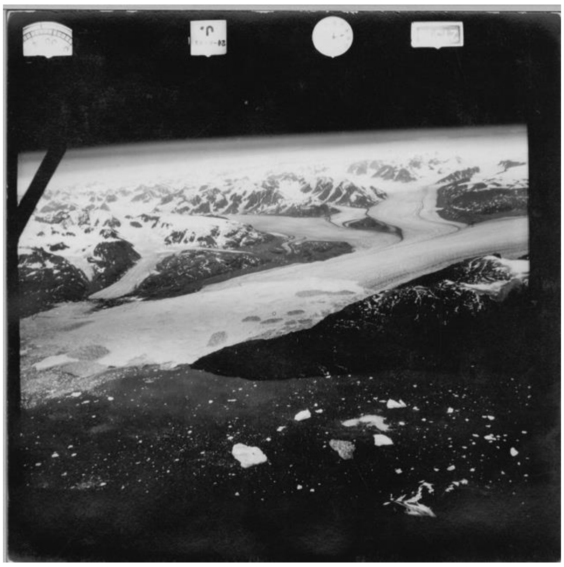
The Research and Measurement Methods Used in Ice Frontiers

In the past few decades, the world has witnessed increasing melting at both poles. This has led to a major debate on how climate change affects the melting of glaciers, and how eventually it might affect sea levels. Scientists have detected significant changes in many of the Ice Sheet's marine-terminating outlet glaciers, which are showing obvious signs of thinning and retreat. So in recent years Greenland, the Ice Sheet and the marine-terminating outlet glaciers have received a great deal of attention. Images and data from satellites and aircraft have played a major role in terms of monitoring the movements, melting and calving of the ice.

Ice Frontiers provides schoolchildren with an opportunity to measure the glaciers, allowing them to experience how the Ice Sheet is reacting to the climate changes we are witnessing today. The programme provides access to some of the climate data, which scientists deploy when estimating the situation, and *Ice Frontiers* sheds light on some of the methods they use to calculate the melting.



Aerial photographs of Kangerlussuaq Glacier from 21 August 1933 (left) and 28 July 2012 (right). The two photos show a difference of about 7 km in the position of the front of the glacier. The photos come from the book, Indlandsisen – 80 års klimaændringer set fra luften *(Photos: The Danish Geodata Agency and Hans Henrik Tholstrup).*

The melting of the ice and mass balance

The Ice Sheet is more than 3 kilometres high. The high altitudes mean that most of the precipitation that occurs here comes in the form of snow. This contributes to the ice mass. In general only the edges of the Ice Sheet are low enough to be affected by warmer temperatures and rain, and this can have a negative impact on the mass balance. The glaciers that account for most of the mass loss from the Ice Sheet are the marine-terminating outlet glaciers. The loss of mass here is due partly to melting of the surface of the ice and partly to glacier calving.

Summer (the ablation period) sees increased solar influence and precipitation in the form of rain, both of which generate meltwater. Meltwater can act as a kind of lubricant at a glacier's sole, and this can cause an increase in the speed of a glacier. When the speed increases, new mass is dragged out from areas deeper within the Ice Sheet, and the Ice Sheet gets lower. If the high speeds continue, a new balance is only possible if the amount of precipitation increases. Increased acceleration makes the front of a glacier less stable, and this can lead to an increased number of calvings. These occur most frequently in the summer when the sea ice no longer forms a protective barrier up against a glacier's front.

The ablation period is short, lasting for only 4 months: from June to September. By August glaciers have lost most mass. Then temperatures start to fall again. This can lead to a renewed, positive mass balance. So scientists are particularly interested in what happens to glaciers by the time we reach the end of the ablation period. Using satellite images captured during the same period every year, they can gain an understanding of mass and glacial front changes from year to year. In *Ice Frontiers* we have selected the same photographic material. For each photo you can see *when* it was taken and *with what*. The earliest photos in *Ice Frontiers*, from the 1940s to the 1970s, were taken from aeroplanes. The new images come from satellites, which circle around the Earth. It is most advantageous if the photos/images come from the same period each year, but sometimes that is impossible. In this case scientists must make do with the photographic material that was taken as close to this moment as possible.

The photos/images are used to show the movements of the glacier front. By comparing them with other climate data and measurements carried out on land, scientists can estimate changes in the mass balance. The work is tricky, because there are a great variety of environments along the coasts of Greenland. Amounts of precipitation, air temperatures, sea temperatures, ocean currents and the topography beneath the ice are among the important factors that play a role in the calculations. However, more factors must be taken into account to achieve the most accurate results possible.

To understand the dynamics of the Ice Sheet and its sensitivity to climate change, we need to look further back in time. Glacial deposits and traces in the landscape, plus core drillings of sediment in lakes and fjords, reveal the movements of the Ice Sheet both during and after the last Ice Age. Like the growth rings of a tree, an ice core also tells the story of what the climate must have been like several thousand years ago. Some aircraft are equipped with laser scanners and radar, which can show the thickness of the ice and the ice layers, and even provide an image of the topography beneath the ice. NASA has collated this data and created a marvellous 3D visualisation of the measurements. You can see it here: Greenland's Ice Layers Mapped in 3D. The measurements have made it easier to find the oldest layer in the ice. They also provide an understanding of why some glaciers accelerate more quickly than others, since the topography, geology and depth of the glacier play a major role in our understanding of a glacier's behaviour.

Measuring glaciers

You can read more about particular glaciers in 'The Glaciers in *Ice Frontiers*'. The six marine-terminating outlet glaciers selected for *Ice Frontiers* are: the Kangerlussuaq Glacier, the Helheim Glacier, Sermeq Kujalleq, the Petermann Glacier, the Upernavik Ice Stream and the Storstrømmen Glacier. They are some of the Ice Sheet's largest marine-terminating outlet glaciers and account for a large portion of the mass loss. Unlike land-terminating outlet glaciers, marine-terminating-terminating outlet glaciers are also affected by changes in sea temperature and dynamic stress. This means they are less stable than land-terminating glaciers. An increase in the rate of calving pulls the ice back until the ice has achieved a balance once again and the front of the glacier has acquired a new stable base.

One of the aims of *Ice Frontiers* is to give schoolchildren the opportunity to try their hand at the methods, which scientists use when measuring the ice and the melting. Consequently, schoolchildren will get an idea of the complexity of Ice Sheet research. That is why we have chosen to use more or less the same tools and climate data, which scientists use. Annual changes to a glacier front are recorded using a reference point, which you position somewhere well into the ice, to be sure that the front of the glacier will not pass it in the course of your measurements. The reference point remains in the same position throughout the measurement process, so you can see the annual changes in the position of the glacier front. The final result will provide a picture, in which you can see all your measurements, and a graph that shows the annual movements. You then compare the graph with other climate data to find out whether they show some of the factors that may have affected the glacier's behaviour. Some glaciers react relatively quickly to changes in temperature and precipitation (within a year), while others take a few years or decades.

Aerial photos and satellite images

The photographic material in *Ice Frontiers* was generated from historical aerial photographs and satellite images. The aerial photos date from the 1940s and after, when Denmark laid claim to Greenland by mapping large parts of the country's coastline. Kurt H. Kjær of the Natural History Museum of Denmark rediscovered these images in the archives of the Danish Geodata Agency. He came up with the idea of using photographic material to show earlier positions of glacier fronts.

Like the satellite images, the photos are perfectly vertical, making it easy to use them for measurements in the programme. However, they were not taken as frequently as the satellite images, so there are only 2-3 years of aerial photographs of each glacier prior to the 1970s.
The satellite images were generated from the USGS website (http://earthexplorer.usgs.gov). 'USGS' stands for the United States Geological Survey, which, in in addition to satellite images, also has access to large amounts of data for environmental conditions and ecosystems, natural disasters, natural resources, land use and climate.

The satellite images were taken from various satellites: Landsat 1-8, ASTER and Corona. The Landsat satellites were launched by NASA in cooperation with USGS, and the images can be downloaded for free from their website (http://landsat.usgs.gov/about_landsat1.php). ASTER is Japanese, but can be downloaded from the NASA website (http://reverb.echo.nasa.gov/) and now also from the USGS website. The satellite images are downloaded in file folders with raw data, which can then be assembled according to your requirements.

Air temperatures

Scientists always try to find a climate station as close to the research area as possible and with the longest possible temperature history. In terms of four of the glaciers, the climate stations are located within a distance of 100 km, while for the last two we have obtained data from sites that are located somewhat further away. This applies to the Petermann Glacier, for which we extracted data from Pitufik (the Thule base) and the Kangerlussuaq Glacier, for which the data comes from Scoresbysund.

The most extensive temperature history comes from West Greenland, because the eastern coast is sparsely populated and is difficult to access due to the sea ice. Below, we list the temperature stations with the Danish Meteorological Institute (DMI) reference number for each glacier:

The Petermann Glacier (4202):	1948 – 2012
The Storstrømmen Glacier (4320):	1949 – 2012
The Kangerdlugssuaq Glacier (4339):	1950 – 2012
The Helheim Glacier (4360):	1895 – 2012
The Upernavik Ice Steam (4211):	1873 – 2012
The Jakobshavn Isbræ (4221):	1873 – 2012

Climate data is updated annually using DMI's technical reports (http://www.dmi.dk/laer-om/generelt/dmi-publikationer/2013/).

Sea temperatures

Sea temperatures have been modelled on the basis of observations and meteorological data from the Met Office Hadley Centre in England (http://www.metoffice.gov.uk/hadobs/en3/).

Precipitation

Precipitation has been modelled on the basis of a combination of precipitation stations from DMI, and from snow and ice cores, by Professor Jason Box of the Geological Survey of Denmark and Greenland (GEUS).

Thematic maps

The data material includes 2 thematic maps. One depicts the speeds of the Ice Sheet in months/years and was created on the basis of satellite data. The other thematic map shows the changes in mass that have occurred since 1900. The map was created by measuring the height of the ice distribution in aerial photos. The aerial photos reveal distinct traces on the fells of how large/high the ice was in 1900, which marked the end of the last Little Ice Age.

***The Research and Measurement Methods Used in* Ice Frontiers** was written by Lisbeth Rykov, MSc in Geography and Geoinformatics (University of Copenhagen). It is based on her thesis: 'Ice Frontiers - A Didactical Method to Convey Scientific Research of the Greenland Ice Sheet to Earth Science in Danish High Schools' (2015).