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An analysis of the spatial and temporal changes on the Jakobshavn Glacier (Greenland) using remote sensing data

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Abstract: This article presents the problem of climate warming and the effect of melting ice caps. The problem of climate warming is discussed in two stages. In the first stage, the factors affecting global warming are discussed in detail and the effects and risks of ablation extensively described. Analyses were conducted on data available online from NASA and Carbon Dioxide Information Analysis Center. The Greenland area (Jakobshavn Glacier) was selected to visualize glacier calving front changes. The analysis of changes was performed on the selected satellite images covering the summer period (June to September) provided by the Landsat program. Then, the changes in the position of the calving front of the Jakobshavn Glacier were visualized for the period 1985–2020, with a repeatability of every 5 years. Thus, our results addressed the challenges of environmental changes to remote sensing data processing. In addition to the visualization, a surface summary of these changes was presented in the study. The results were discussed in the context of climate change data processed by means of the GIS method. Furthermore, an analysis of the effects of greenhouse gases on glacier surface changes was performed. In summary, the results reveal that satellite imagery is an excellent source of data on which to visualize glacier calving rates, comparing individual layers showing the position of the glacier calving front and calculating the area of calved ice.

Keywords: global warming, glaciers, ablation, glacier calving, remote sensing, Greenland

INTRODUCTION

Climate warming and the associated melting of ice caps have been one of the major concerns of 20th century. Despite the continuous evolution of our planet's climate, the rate at which it is currently changing is particularly impressive. Glaciers and ice sheets are the most visible evidence of global warming. The melting of the ice caps, in addition to significantly raising the level of the waters of the All-ocean, affects weather changes all over the world. An example of continuous temperature rises in the Bartin province located in the western Black Sea Region of Turkey has already been provided elsewhere (Yaman 2020).

This research addresses two issues, discussed in two parts. In the first part, the problem of the melting of the ice caps in the world is considered. The main factors responsible for this phenomenon, including the influence of greenhouse gases, associated threats and potential consequences are visualized. A particular focus is placed on Greenland, which is the world's second largest area covered by ice.

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In the second part, special attention is given to the issue of glacier calving. Calving causes ice to weaken, and thus the phenomenon is becoming more regular and dramatic. This part also focused on Greenland, namely the Jakobshavn. Glacier located in the southwestern part of the island. The satellite images depicting the retreating glacier front over a period of 35 years were processed to show the rate of calving. Vectorization of the calved ice area was performed on the individual raster files, which allowed for accurate area calculation and numerical representation of the results. Based on the performed visualizations and calculations, as well as archival climate records from the periods studied, the analysis of changes in the position of the calving front of the Jakobshavn Glacier between 1985 and 2020 was made.

THE PROBLEM OF MELTING ICE COVER

All processes that reduce the mass of a glacier are referred to as ablation and they include melting, evaporation, sublimation, or calving. The global warming caused by the increase in the Earth's average temperature largely contributes to ice melting and the main causes of global warming are diverse in origin.

Life on Earth depends on a balance that can be very easily disrupted. Despite the ability of humans to adapt to different environmental settings, humans constantly change natural environment by improving their living conditions through technological advances. One of the many negative effects of industrial development is the rise of the global average temperature on the Earth. It is widely believed that it has increased by 0.6°C since the beginning of the 20th century, while the projected temperature increase in the 21st century is between 1.5°C and 4.5°C. The greatest temperature change is expected in Europe, North America and northern Africa. While changes between 1901 and 1945 can be attributed to natural variations in solar radiation, warming after 1975 is caused by human activities (Benestad 2008).

Ice melting is a direct consequence of these increased temperatures and significant ice loss has been observed in both the Arctic and Antarctic. Furthermore, mountain glaciers are gradually disappearing from both polar regions and tropical areas such as Kilimanjaro, New Guinea and the Andes (Arthus-Bertrand 2021). Surface water inflows are also disappearing, and this in turn affects freshwater ecosystems (Marchina et al. 2020).

Factors affecting ice melt

The main reason for the increase in the Earth's temperature is the emission of the greenhouse gases into the atmosphere. The largest quantity of carbon dioxide is produced by combustion. The second most important gas that is delivered into the atmosphere is methane. These gases are released into the atmosphere by transportation (Chocholac et al. 2021), industry (Shaw et al. 2021), agriculture and animal husbandry (Calciolari et al. 2021).

Water vapor is mainly formed by increased evaporation of ocean water in the intertropical zone. It traps the sun's radiation reflected from the Earth's surface in the upper atmosphere, thus storing heat. The greenhouse effect, which stands behind the origin of life on Earth and ensures that the average temperature remains at 15°C, in its current, intensified form has led to global warming. Studies of air bubbles, trapped for years under ice caps, have shown that compared to the time before the Industrial Revolution, the concentration of greenhouse gases increased to a value unprecedented for more than 20 million years (Arthus-Bertrand 2021). Analyzing the period of the last millennium, we can see that initially the content of both carbon dioxide and methane remained constant with small annual fluctuations (about 280 ppm and 700 ppb, respectively). A particular increase occurred as early as the beginning of the 19th century, along with the acceleration of the process of industrialization and has been steadily increasing up to the present. This rapid increase has resulted in a 33% increase in carbon dioxide and a 64% increase in methane compared to the year 1000 (Fig. 1).

Many reports have focused on assessing the amount and degree of carbon dioxide effects. The development of the interpolation algorithms that evaluate the amount of CO_2 for a given study area has been described in previous reports (Bezyk et al. 2021). This paper evaluates the level of air pollution in an urban environment near Wrocław, Poland.

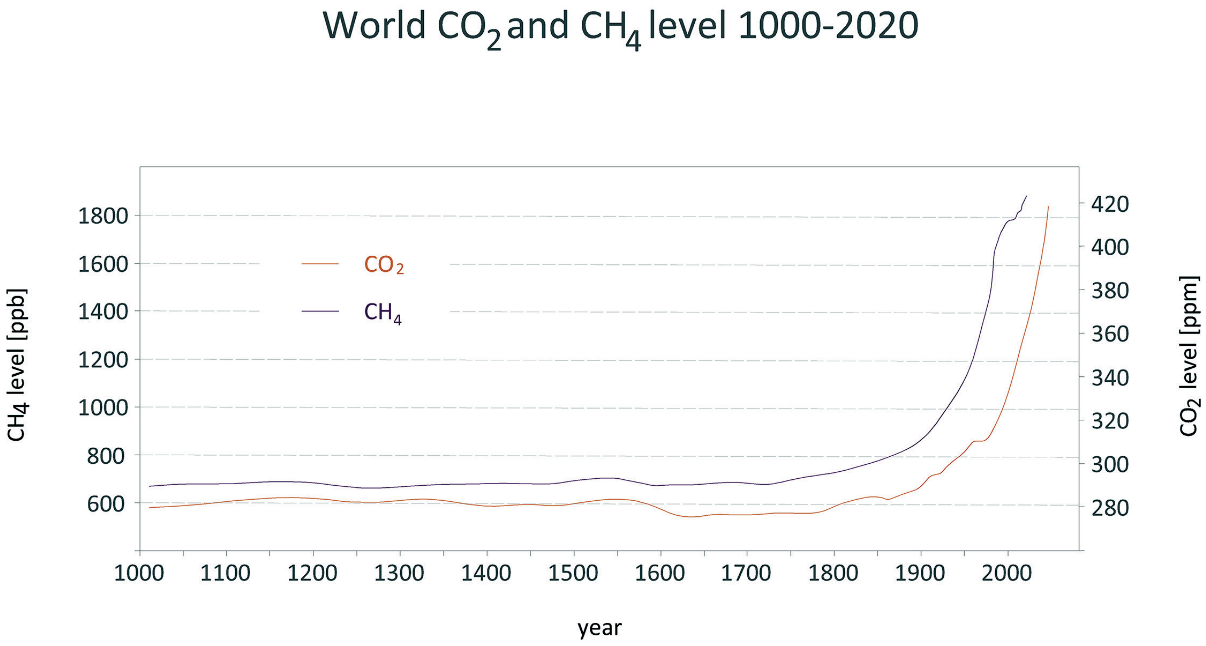


Fig. 1. *Global levels of carbon dioxide (CO_2) and methane (CH_4) between 1000–2020 years. Authors' analysis based on Law Dome DE08, DE08-2, and DSS records made available by Carbon Dioxide Information Analysis Center (n.d.) for 1000–1958 years and data from NASA: Climate Change and Global Warming (n.d.) for 1958–2020 years*

The emission of gases from industry cause more complex problems for the climate. Among others, these include the increase in temperature besides the greenhouse effect. For instance, the sulfur emissions produced by the industry cause a decrease in temperature. On the other hand, ozone contributes to the intensification of the greenhouse effect. However, the hole in the ozone layer which has been observed in the high parts of the atmosphere, especially over the Arctic, has a decreasing effect on temperature (Arthus-Bertrand 2021). Moreover, the negative effects from the fluorinated greenhouse gases on climate change have been discussed in an article (Castro et al. 2021) where waste management strategies to mitigate the impact of these gases are considered.

Another problem consists in the color of glacial ice, which is very rarely completely white. Usually, the huge volumes of moraine contained in the ice make it difficult to distinguish the glacier from the surrounding rocks. Often the ice is also covered with what is known as cryoconite, dust blown in from both surrounding areas and distant lands. For example, dust from the Sahara can reach as far as the Greenland ice sheet. Many pollutants are found on glaciers, which include pesticides and microplastics. It is important to remember that glaciers are also habitats for organic matter. The algae which develop on the surface of the ice have a pigment that protects them from high doses of UV radiation. Their blooms therefore change the color of the glacier. All of the mentioned above factors are contribute to the darkening of the ice and consequently to the reduction of albedo – the ability of the surface to reflect solar radiation. A glacier with a darker surface absorbs more radiation than it reflects, leading to an increased rate of melting (Myers & Ribergaard 2013).

Effects and risks of ablation

The first notable consequence resulting from the melting ice consists in an increase of the volume of ocean water. Since the beginning of the 20th century, sea levels have risen by 10–20 cm (Fig. 2). It is predicted that before the end of this century, the increase in sea level may be an additional 11–17 cm. This process may result in intensified natural hazards such as floods and coastlines may also undergo significant changes. Some areas, for instance river deltas, may disappear completely from the Earth's surface, along with intensified processes of the shoreline erosion (e.g., the break-up of riffles) (Cooper & Smith 2019).

If the entire ice sheet were to melt, it is estimated that the level of the total ocean area would rise up to by nearly 80 m (Marcinek 1991), which would submerge most of the east coast metropolitan areas of the United States, vast areas of Asia with cities such as Hong Kong and Shanghai, and many European capitals. It is believed that an intra-continental sea within Australia could also arise.

Another aspect of ablation includes of the shifting of the borders of climate and vegetation zones. Along with the gradual disappearance of the ice caps, climate zones are shifting toward the poles. More and more areas of permafrost are thawing, creating vast marshes, maquis reach higher latitudes, farmers in temperate zone countries begin to cultivate African varieties of plants. This phenomenon can also be observed in Poland: the vegetation period is becoming longer, the winter period is being delayed and winter temperatures are decreasing, with less snow coverage. Besides vegetation, climate change also affects fauna. Many animal species depend on polar climate ecosystems as their usual habitats. Global warming poses a threat to polar bears, seals, some species of foxes and wolves, which, in the worst-case scenario, are threatened with extinction. Climate change is not only a risk for the polar world – it also negatively affects coral ecosystems, which are abandoned by algae living in symbiosis with them as a result of rising temperatures, causing them to turn into white, dead skeletons.

Another consequence of the melting of the ice caps is that the land underneath lifts as part of the phenomenon known as isostasy. Parts of Greenland and Antarctica are currently below sea level, which could change when the ice melts and lifts them back up. It is probable that as a result of glacial isostasy, land level moved after the complete or even partial melting of ice would cause the disappearance of current water connections between the seas, or the transformation of bays into lakes (Marcinek 1991).

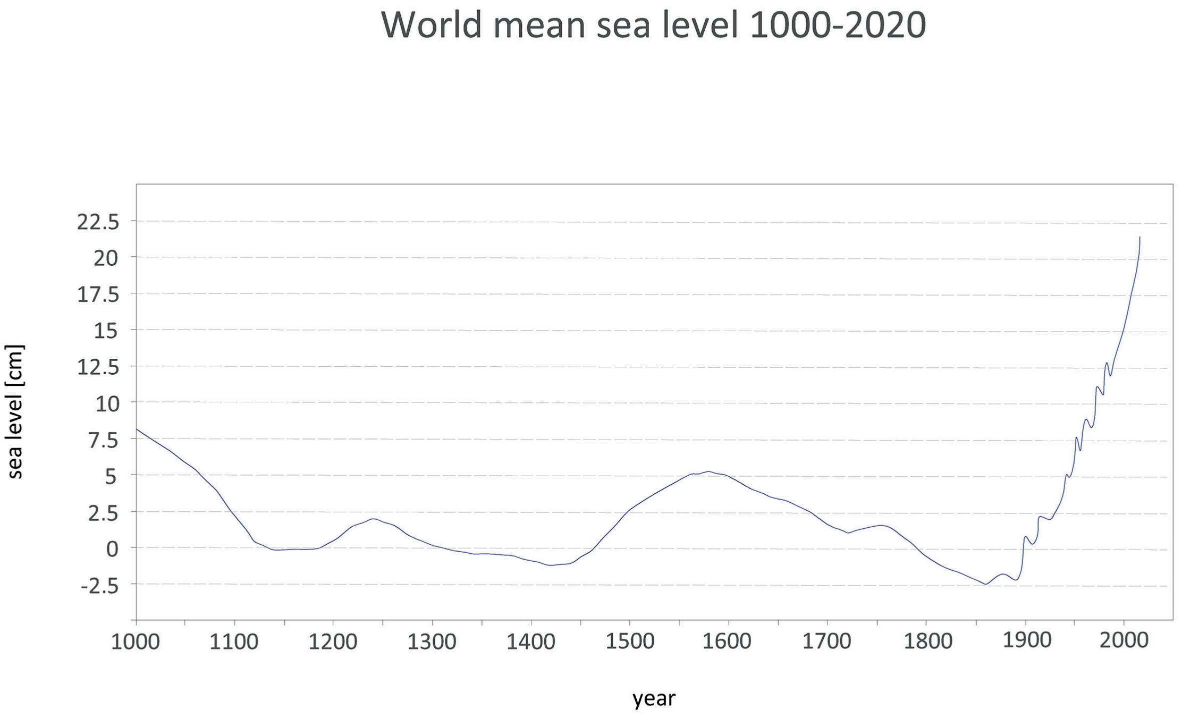


Fig. 2. *Global sea level [cm] from 1000 to 2020. Prepared from data: Kopp et al. (2016) – for years 1000–1890, Church & White (2011) – for years 1890–1993, The 2 Degrees Institute (n.d.) – for years 1993–2020*

Currently, the total surface of the ocean is crossed by a series of submarine currents caused by the difference between the salinity in various parts of the ocean. Land masses and glaciers store the largest reserves of fresh water on Earth. Their melt, followed by the influx of such a huge mass of fresh water into the oceans, would disrupt the direction of currents, which play an important role in the transport of nutrients necessary for the existence of animals. The climate of coastal areas which create habitats for marine species depends on them. For example, the warm Gulf Stream, which is rapidly disappearing, may cause temperature changes in the northwestern part of Europe which would results in disappearance of certain types of cereals and may trigger their migration (Hakai Magazine, n.d.).

The calving of glaciers

Another process that causes ice cover to reduce is glacier calving. Calving is the breaking off of glacial ice blocks from a glacier body located in or bordering a water body (Jaroszewski et al. 2018). It is a natural process that features in the life cycle of every glacier, but only to a certain extent. The increasing phenomenon of global warming makes ice sheets less resistant to external factors such as wind or water erosion. As a result, unstable ice is cracking and breaking apart, forming icebergs at an increased, alarming rate.

Calving, which is the cause of more than half of the ice mass lost from the Greenland and Antarctic ice sheets, is one of the most noticeable and yet least understood of all the processes that occur within glaciers. Despite the significant role it plays in the ice mass balance, a satisfactory mathematical model to describe this process has not yet been developed (Bassis 2011). Originally (1991) it was modeled using relationships linking the calving rate to water depth at the front. Later on (1996), a theory was advanced that the glacier calves when the height of the ice cliff reaches a critical point. However, none of the above empirical models were able to describe the entire process of glacier behavior. In the current 2014 models, calving is predicted to occur when surface crevasses propagate to sea level (Murray et al. 2015). Despite many case studies (Trabant et al. 2003, Mohajerani et al. 2019) defining general trends in the behavior and performance of ice, calving still remains a major problem for glaciologists.

In summary, there is a significant correlation between calving dynamics and changes in the temperature of the aquatic environment surrounding a given glacier, both near the surface and in the deeper strata of the ocean. The rate of glacier disappearance and calving is significantly higher for tidal glaciers, i.e., those whose front has a boundary in the sea (Bassis 2011).

REMOTE SENSING AS A TOOL FOR MEASURING ICE MASS BALANCE

The mass balance describes change in the glacier mass over a given period of time. The most frequently selected time span is a year, where the difference between total ice accumulation and ablation occurring in a given year can be analyzed, or a season (winter/summer), where the difference at the beginning and end of the season is studied (Małecki 2015). The mass balance has a positive value when the mass gain is greater than the loss and the volume and area of the glacier has increased. When ablation exceeds accumulation, the balance is negative, while an equilibrated balance occurs when the gain is equal to the loss. Particularly pronounced changes in the ice mass volume occur when glacier fronts melt, which is even affected by short-term climate fluctuations. The occurrence of large-scale climate change, such as global warming, leads to the formation and complete disappearance of glaciers and ice sheets. The occurrence of large-scale climate change has been used as a benchmark for glacial and interglacial epochs. With the exception of the periglacial areas, variations in glacier front extent depend on a given season – such as winter accretion and summer ablation. Diurnal and multi-day, or in some cases annual, fluctuations are the result of weather changes. All longer fluctuations of the size of glaciers are caused by climate changes, with the exception of seasonal fluctuations controlled by the weather. The trend of decreasing ice cover over the last century does not exclude oscillations and temporal increments over selected years, a fact confirmed by the analysis in this study.

The variations in the range of glaciers also extend over the areas for several centuries, as exemplified by the Little Ice Age, lasting roughly from 1550 to 1900, when glaciers repeatedly expanded to their maximum extent. This is documented by the presence of sizable terminal moraines in the Alpine region from 1770 to 1850, formed much lower than the modern marginal zones of the glaciers. Earlier periods also recorded moments of increased glacial extent, for instance during between 1000–1200. After 1900, the Little Ice Age has been seen to retreat as a result of the ensuing warm phase. It has been characterized by the retreat of glaciers, interrupted by the momentary advances of individual glaciers (Marcinek 1991).

Although satellites have been providing valuable information on remote polar regions since 1960s, it was not until the release of Thematic Mapper (TM) sensor satellites (i.e., Landsat 4 and Landsat 5) that detailed information on areas permanently covered by snow and ice has been available. These images have twice the spatial resolution (15 m) of those acquired with the Multispectral Scanner Sensor (MMS) and are often used for major glaciological studies. Compared to MSS, the newer sensors (TM, ETM+, OLI, or TIRS) are good at distinguishing snow, ice, and water from clouds because they have a higher albedo. As a result, they will appear much darker than clouds on Shortwave Infrared (SWIR) channels, which the MSS sensor lacks (Orheim & Lucchitta 1987).

A negative ice mass balance has been observed during the last century. Although satellite gravity surveys do not indicate a drastic acceleration of the ablation rate since 2013, as was the case in the beginning of the 21st century, the balance result remains consistently negative. As a result, there is a constant need to measure and evaluate ice sheet change using tools such as satellite remote sensing. For several decades, sensors on board satellites operating at different wavelengths of electromagnetic radiation have been observing the Greenland ice sheet. The first measurements of the ice sheet height from space were made in the 1970s by radar altimeters installed on satellites belonging to NASA: GEOS-3 (Geodetic and Earth Orbiting Satellite-3) and Seasat (one of the first Earth-observing satellites designed to gain a better understanding of the behavior of seas and oceans) and the U.S. Navy-owned Geosat (Geodetic Satellite). More recent radio altimeter missions, used for mapping changes in the ice sheet height, are carried out by GFO (Geosat Follow-On), ESA (European Space Agency) ERS-1 and ERS-2 (European Remote-sensing Satellites 1, 2), EnviSat (Environmental Satellite), and CryoSat-2 (Cryosphere Satellite-2). Radar altimeters mounted on board the satellites, indicating the actual altitude of the flight based on measurements of the return time to the aircraft of the signal reflected from the Earth's surface, are capable of detecting even the smallest changes in the height of the ice. Radio altimeter missions currently provide the largest record of changes in the volume of the Greenland ice sheet (Cooper & Smith 2019).

STUDY AREA: JAKOBSHAVN GLACIER

Jakobshavn (locally called Sermeq Kujalleq) is Greenland's largest glacier located on its west coast near the town of Ilulissat (Fig. 3).

Jakobshavn, a UNESCO World Heritage Site, is one of many Greenlandic glaciers belonging to the outlet type, meaning that it forms part of the main ice sheet. It is considered one of the fastest moving glaciers, with speeds of up to 7 km per year near the calving front (Sohn et al. 1998). It covers an area of 110,000 km^2 and drains about 6.5% of the ice sheet (Joughin et al. 2004). It produces more than 10% of Greenland's icebergs, begin the largest contributor to the Greenland ice sheet mass fluctuations over recent years. The observed changes in the ice volume of the Tern and the retreat of the front of Jakobshavn, as well as in other similar glaciers in Greenland, have raised questions regarding the processes controlling the stability of the Greenland ice sheet (Weidick et al. 2004).

In 1850, near the end of the Little Ice Age, the Jakobshavn calving front extended approximately 35 km further than the current summer minimum. Over the next century, repetitive retreats moved the glacier front 20 km in land, where its position finally stabilized in the 1950s. For the next 50 years, the calving front remained relatively stable, with only seasonal fluctuations of about 2.5 km. Since the late 20th century, the glacier tended to lose mass (Joughin et al. 2008).

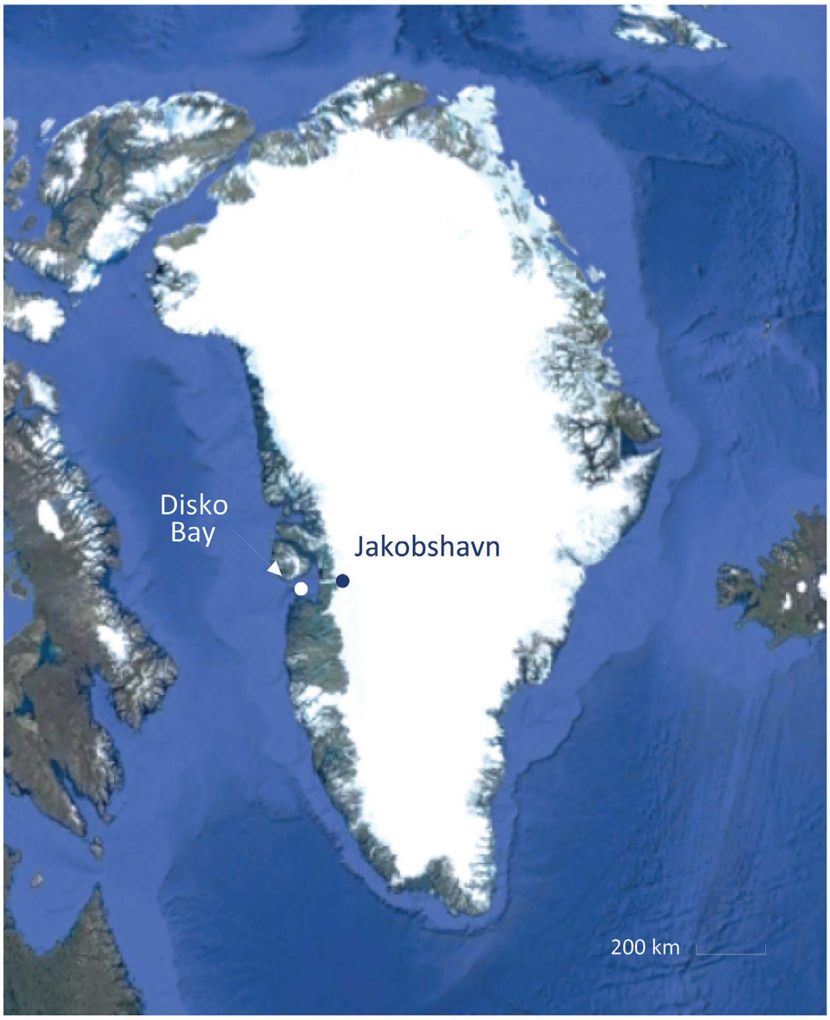


Fig. 3. *Location of the Jakobshavn Glacier*

The first mapping of the glacier area was done by the Danish geologist Hinrich Johannes Rink in 1851. Attention to the rapid movement of the glacier came in 1875 (Helland), along with seasonal fluctuations of the glacier front being recorded by surveys conducted between 1879 and 1880 (Hammer). Regular meteorological surveys have been in operation in Ilulissat since 1873 (Weidick et al. 2004).

In the present study, we evaluated and visualized changes in the position of the calving front of the Jakobshavn Glacier over the period 1985–2020. These changes were detected by means of the satellite images acquired by the Landsat satellites and made available by the United States Geological Survey (USGS) website (USGS.gov, n.d.). The report shows a trend of the retreat of the glacier's tongue and a decrease in the ice surface.

VISUALIZATION AND ANALYSIS OF CALVING IN THE JAKOBSHAVN GLACIER

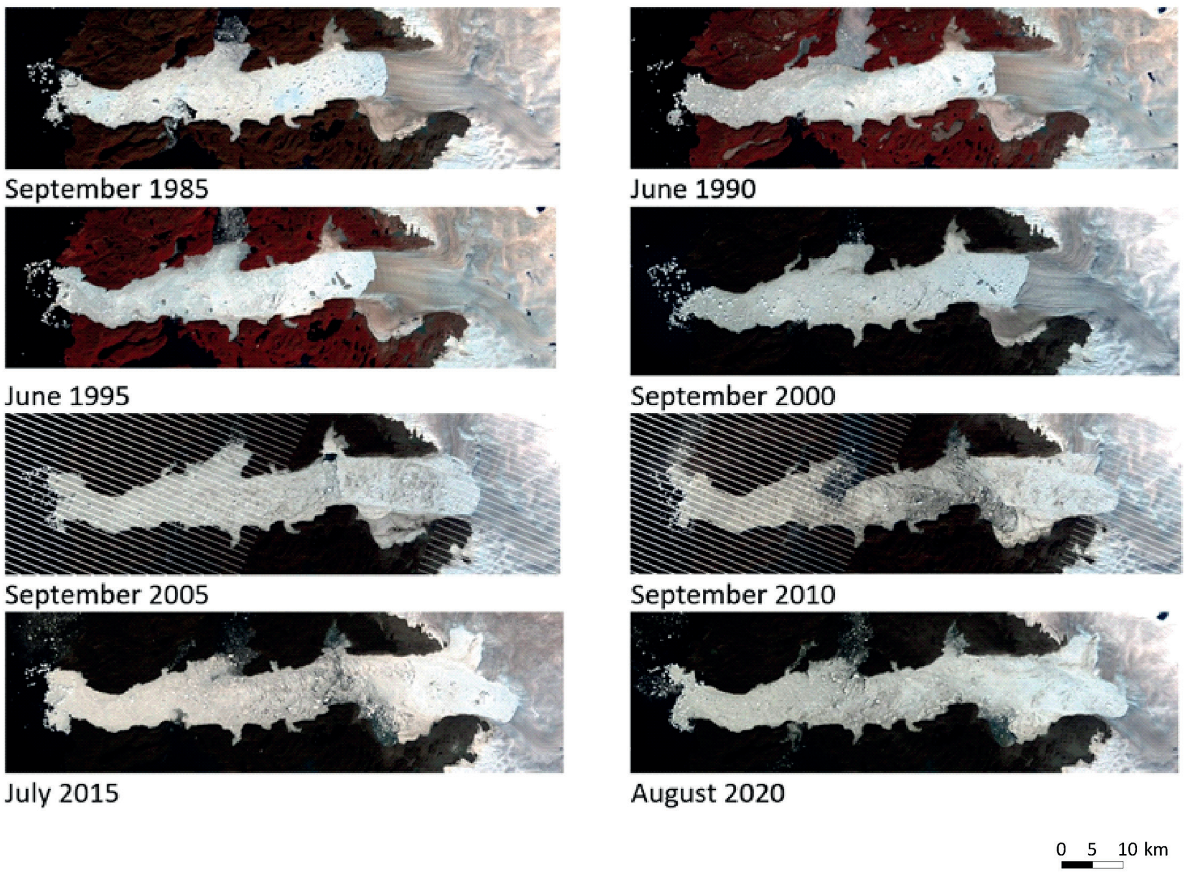
Today, remote sensing data are widely used in various research disciplines. They play a key role in detecting climate change, helping to evaluate natural disasters, improving forest management by documenting the locations of fire outbreaks and aiding the assessment of the impact of fires on the forest ecosystem. Moreover, satellite images are applicable in the domains of water management, urban development, energy, carbon assessment, and agriculture. Therefore, satellite images were applied in this study to assess the calving of the glacier, over a period of a dozen years.

In order to evaluate the shift in the calving front of the Jakobshavn Glacier, eight Landsat satellite images from 1985–2020 were selected with a time interval of 5 years. The climate in Greenland strongly reflects the annual cycle of melting and glaciation, which explains the time of the image capture during summer months, from June to September, in the peak of the Greenlandic summer. After defining the coordinates of the area and the maximum cloud cover (20%), the following data set of satellite images was selected: 5.09.1985 – Landsat 5 MMS, 22.06.1990 – Landsat 5 TM, 20.06.1995 – Landsat 5 TM, 13.09.2000 – Landsat 7 ETM+, 4.09.2005 – Landsat 7 ETM+, 18.09.2010 – Landsat 7 ETM+, 29.07.2015 – Landsat 8 OLI + TIRS, 11.08.2020 – Landsat 8 OLI + TIRS.

The selected sets of satellite scenes were processed and the data integrated to one coordinate system WGS 84 / UTM zone 22°, defined for the Greenland area between 54°W and 48°W. Additionally, atmospheric correction DOS1 – Dark Object Subtraction was applied, which helps to estimate the reflectance of the Earth's surface. The next step included the creation of the color composition of the study area. The selection of channels is explained by the wavelengths similar to the range of wavelengths of light visible to the human eye, i.e., 0.38–0.75 μm (Red, Green, Blue). The generated RGB images are presented below (Fig. 4).

Calving areas from each year were vectorized, and then the area of calved ice for each year was calculated. Due to the difficulty of vectorization in areas where large numbers of individual pieces of ice float, the accuracy of the calculation was set to 1 km^2. The results of the calculations are summarized in the table below (Tab. 1), while the example of vectorization, performed on the raster color composition of the calved ice area of the Jakobshavn Glacier from 1985, is provided below (Fig. 5).

Comparing the area of ice that has broken away from the front quantitatively shows changes in the glacier area over the given time span.


September 1985

June 1990

June 1995

September 2000

September 2005

September 2010

July 2015

August 2020

***Fig. 4.** Glacier calving front at different time periods*

Table 1
Calved ice areas for 1985–2020 [km^2]

Year	1985	1990	1995	2000	2005	2010	2015	2020
Area [km^2]	373	349	353	377	525	532	567	558

Fig. 5. *Vectorized area of calved ice of Jakobshavn Glacier from 1985*

Mapping the Jakobshavn Glacier by means of satellite images over 35 years allows the interpretation of the changes that have occurred within the calving front. Apart from two cases where the mass of the glacier has increased compared to the previous studied period, namely 1985–1995 and 2015–2020, the ice area today (2020) covers a much smaller area than a few decades ago, which allows us to conclude that there is a general trend of melting ice cover.

In the next analysis, the individual rasters were overlaid, and the glacier ice sheet boundary was then marked by a colored contour line on each of the rasters. All the lines were put together on the background of the 2020 raster, which visualizes changes in the position of the glacier, and its calving front (Fig. 6).

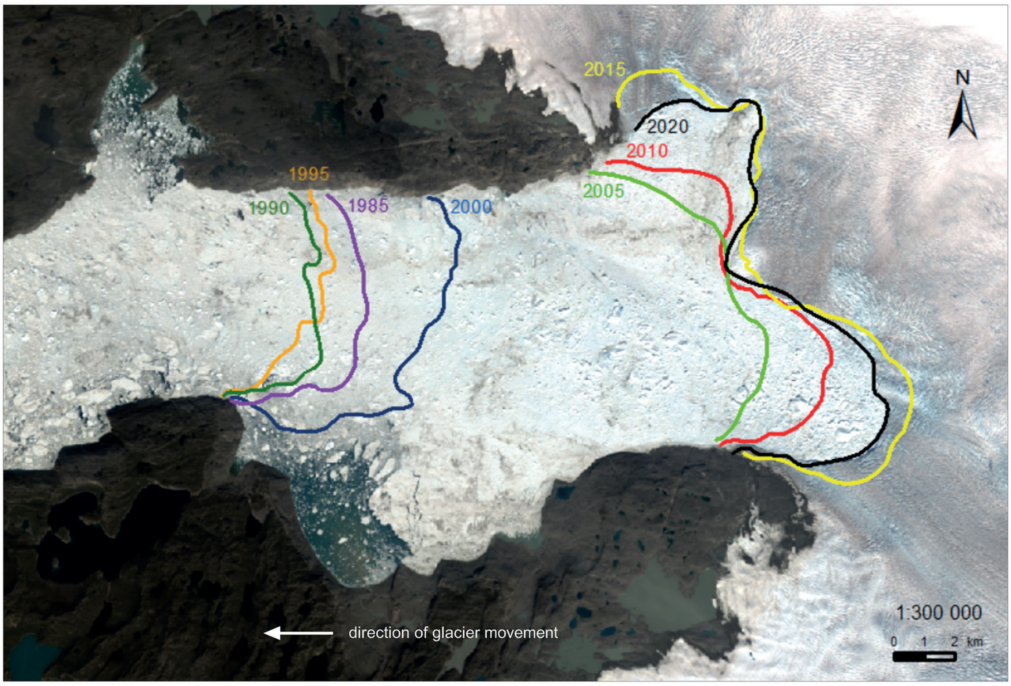


Fig. 6. *Change in the calving front of the Jakobshavn Glacier*

Interpretation of the position of the lines constituting the boundaries of the glacier tongue and the calculated areas calved from the ice face in the following years: 1985, 1990, 1995, 2000, 2005, 2010, 2015, 2020 allows us to make the following statements:

- From the beginning of the studied period until 2020, the ice mass of the Jakobshavn Glacier has decreased, while the calving front has retreated. The area of the calved ice has increased by 185 km^2, thus the area of the glacier has decreased by this amount.
- Between 1985–1995 and 2015–2020, we detected a change in the overall trend of the ice to melt/recede from the main massif, with the glacier gaining mass during these years. The area slightly increased (20 km^2 for the first period and 9 km^2 for the second one).
- At the beginning of the 21st century, between 2000 and 2005, the biggest difference between the position of the calving front was registered. It retreated several times more than it did for the other analyzed periods. The glacier area decreased by as much as 148 km^2 (to compare, in 2010–2015, when the second most intense calving period occurred, the area decreased by 35 km^2).

DISCUSSION AND ANALYSIS

Annual fluctuations in melting, freezing and calving are controlled by many interacting factors. The immediate and most obvious reason for the ice melt is the increase in air temperature, which in turn depends on the increase in atmospheric concentrations of greenhouse gases. The loss of Ilulissat glacier ice is largely a response to the changes in global temperature trends (Figs. 7, 8).

The data shown in the graphs above demonstrate the large impact that constant increases in two of the major greenhouse gases (CO_2 and CH_4) are having on the Earth's climate. Over the period of 35 years (1985–2020), carbon dioxide and methane levels have risen by 65 ppm and 225 ppb respectively, while the temperature anomaly relative to average temperatures over the 1951–1980 period is +0.99°C.

Analysis of data collected by NASA's GRACE and GRACE Follow-On satellites shows a regular decrease in the Greenland ice mass over the current century, with small annual variations associated with seasonal changes. Over the last 20 years, the volume has decreased by 6000 Gt (Fig. 9).

However, in order to accurately analyze changes in the Jakobshavn Glacier area since 1985, it is necessary consider local factors that determine its calving and mass gain rates. Historical measurement data from 1979–2018 realized by the Copernicus Climate Change Service (Copernicus) and visualized by the Lobelia Earth service as a climate bar for the Jakobshavn Glacier (50°W; 69°N) show a certain correlation between the variability in calving intensification and air temperature (Fig. 10). When interpreting the visualization, the higher intensity of the red color shows a higher value of the average temperature for a given year, while the blue colors and hues means the lower temperature.

In the changes in mean temperatures in the individual years, the similarity in changes in the position of the Jakobshavn calving front can be found. Deviations from the general tendency of the glacier to retreat and lose mass are found when analyzing the climate bar. Temperatures in 1990 and 1995 were lower than in 1985, which explains the phenomenon of slow ice mass gain during this period. The period of 2000–2005 demonstrated the maximal retreat of glacier front, but this is not confirmed by the analysis of temperatures, which only increased by 0.7°C. Changes in atmospheric circulation in the North Atlantic region have had a direct effect on the circulation trends of water in the ocean.

In order to accurately explain the trends in the detected calving front changes, special attention should be paid to the dynamics of the ocean currents. The sudden retreat of the glacier front, causing the intensification of calving, is attributed to the influx of the relatively warm and salty water of the Irminger Current along the west coast of Greenland. This has caused the cold water flowing into Disko Bay (into which Jakobshavn enters) to significantly warm by about 1–2°C since early 1990s. Although Irminger water has been present in Disko for many years, it has been observed to have a major influence on the climate of the entire bay since 1997 due to the increasing temperatures and salinity.

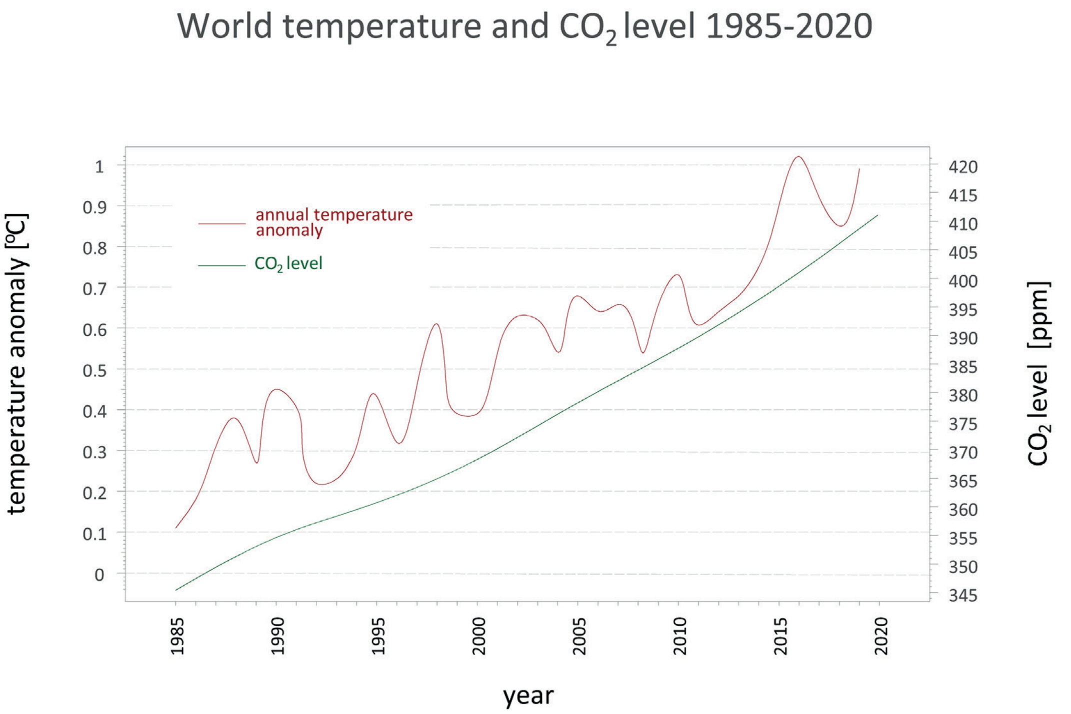


Fig. 7. *Correlation between the temperature rise and carbon dioxide levels. Own compilation based on NASA: Climate Change and Global Warming (n.d.) and National Oceanic and Atmospheric Administration (n.d.)*

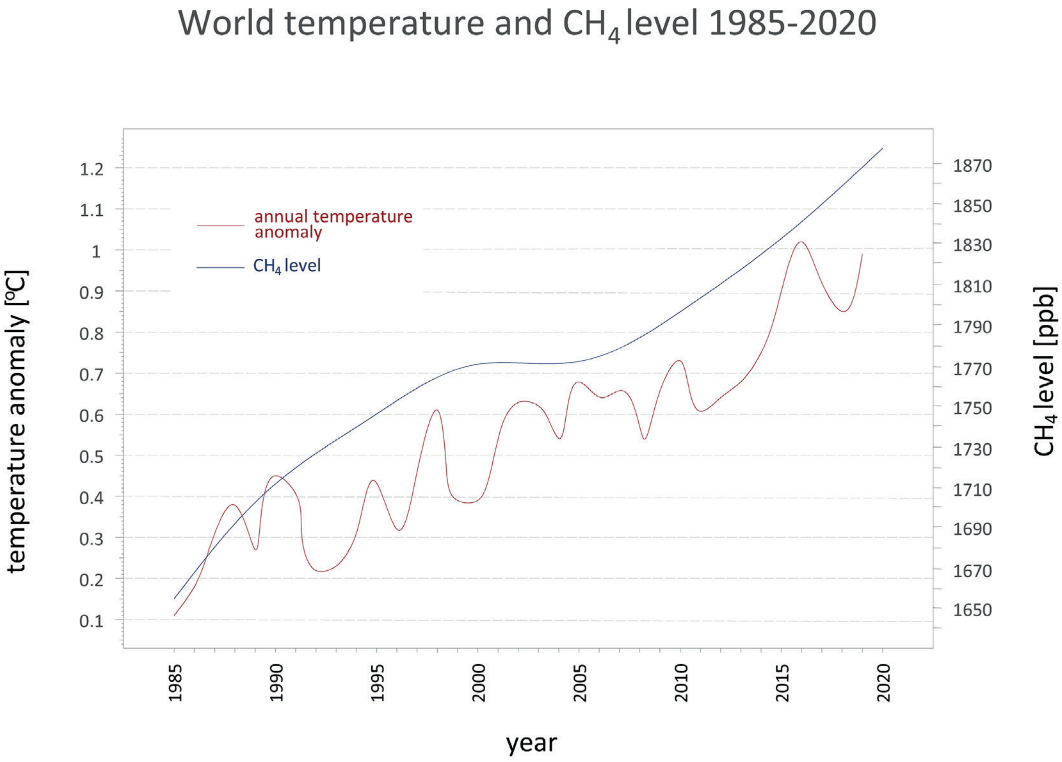


Fig. 8. *Correlation between the temperature rise and methane levels. Own compilation based on NASA: Climate Change and Global Warming (n.d.) and National Oceanic and Atmospheric Administration (n.d.)*

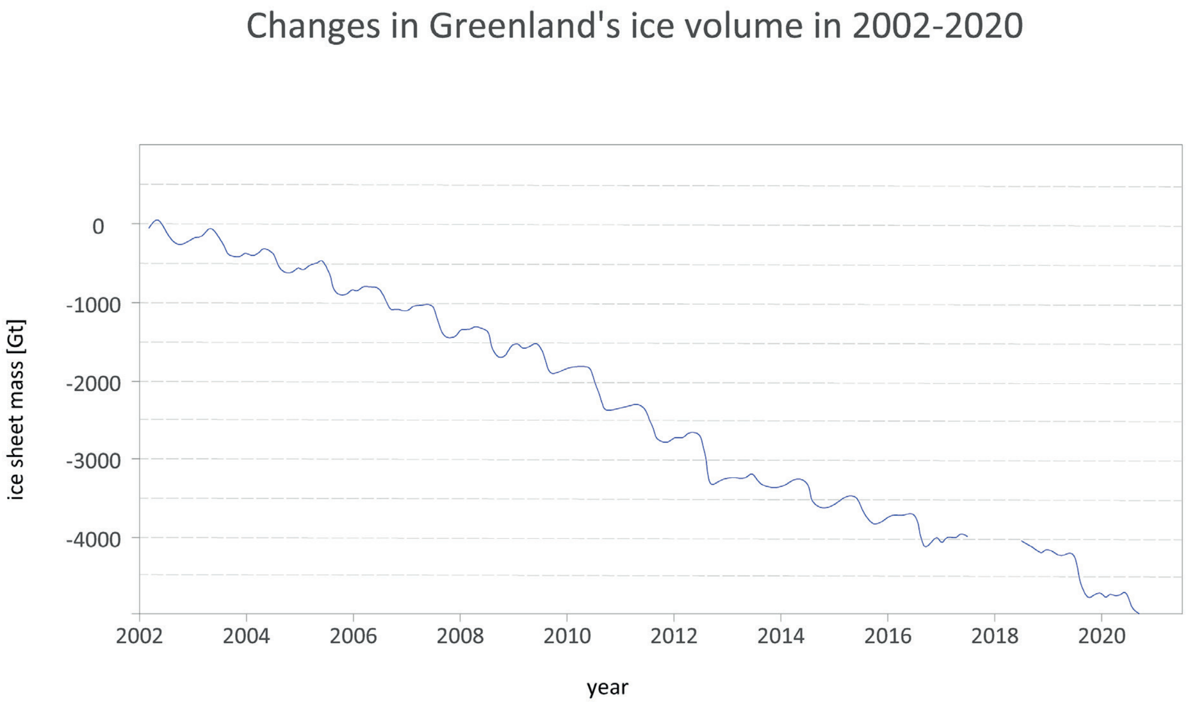


Fig. 9. *Changes in Greenland ice sheet volume from 2002 to 2020 (based on NASA: Climate Change and Global Warming, n.d.). The gap in the graph represents the time between each satellite mission*

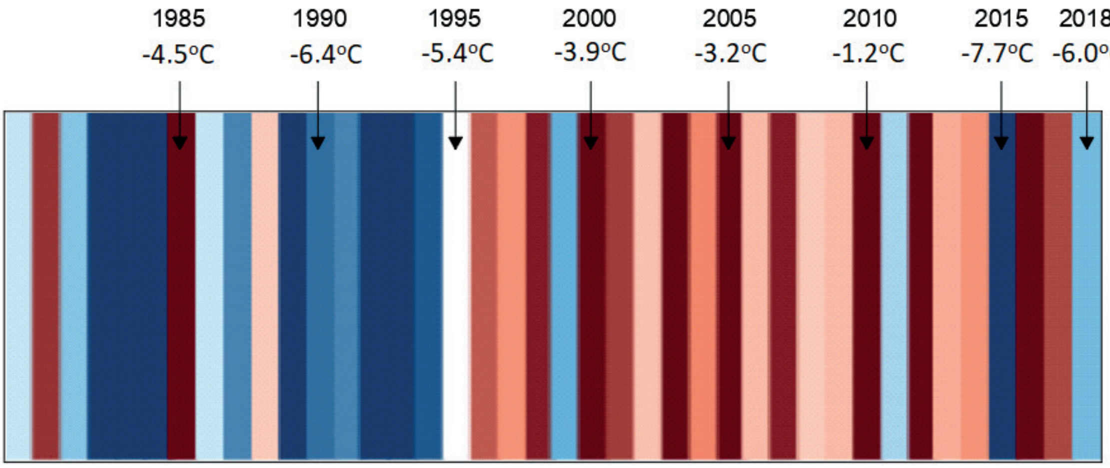


Fig. 10. *Climate bar for the Jakobshavn Glacier area, 1979–2018 years. Own compilation on a bar created by the Past Climate Explorer tool of the Lobelia Earth website (Past Climate Explorer, n.d.)*

The waters of the Disko Bay are divided into the three vertical layers. From the water surface to about 30 m deep, fresh water from melting ice stands out, and is most susceptible to seasonal variations in air temperature. The layer of polar waters is considered to be ~30–200 m deep, while in the deepest parts the bay is marked by warmer and saltier water, which results from the mixing of waters originating from the Atlantic Ocean with cooler Arctic waters modified by local inflows.

Below this thin, 30-m layer, significant temperature fluctuations are observed, with a strong predominance of warming. Based on the averaged data for Disko Bay, during the late 1985–1990s, as was the case between 2000–2005, the water at the surface reached 4°C, but already cooled to about 2°C at a depth of 10 m, while later it cooled to 2°C at as low as 30 m. In the second half of the 1980s, water temperatures reached below 0°C between 20 and 150 m, while in the early 2000s no negative temperatures were recorded along the entire section. In the deeper parts of the bay, around 300–700 m, the maximum temperature was 2.5°C during the first analyzed period, five years later it increased to 3.5°C (Myers & Ribergaard 2013). All the above-mentioned changes may have had a direct impact on the exceptionally intense ice calving between 2000 and 2005.

Over the next five years, 2005–2010, the ice retreated much less compared to the previous period, which is not clearly visible in the analyses of the historical climate records at the time. The 2010 water temperatures approached those of the late 1990s, when glacier started to retreat. This anomaly is explained by an increased influx of cool waters from the side of Baffin Bay, a nonlocal atmospheric variation (Kajanto et al. 2020). In the following years, the waters of Disko Bay became relatively warmer, above 3°C, which was reflected in the acceleration of the calving of Jakoshavn in 2012–2015 (Joughin et al. 2020).

Despite the lack of the reliable retrospective data, the current size of the Jakobshavn Glacier is considered to be close to its minimum for the entire Holocene era. However, a gentle increase in glacier mass has been detected over the last 5 years (2015–2020), indicating that the trend of rapid retreat may have reached a turning point (Kajanto et al. 2020).

In the fall of 2016, the glacier front slowed retreating again. The temperature recorded at that time at a depth of about 250 m in Disko Bay dropped to ~1.5°C, in contrast to the air temperature. Indeed, 2016 is recorded as the warmest year in recent decades for the Jakobshavn area, with an average of –3.1°C. Until the spring of 2019, the rate of winter mass accretion exceeded the rate of summer melt, which resulted in the calving front moving along in the direction of the trough (Joughin et al. 2020).

CONCLUSION

The current state-of-the-art regarding the aspects of the environment, both its past and present state as well as methods for its effective management, is still not reliable enough. To date, it has not been possible to precisely predict the rates of global warming over the next few years. Predictions made on the basis of computer models can differ significantly, precluding them from any consideration in precise and accurate models. However, the fact remains that since the middle of the 19th century, i.e. after the end of the Little Ice Age which lasted about 400 years, the Earth's climate has been warming. It is believed that since the beginning of the 20th century, the average surface temperature of the Earth has increased by 0.6°C. The key factors affecting the rise of the temperature have anthropogenic origins. However, the balance between the human and natural aspects in global warming is still both doubtful and debatable. The analyses of the atmospheric concentrations of some greenhouse gases presented in this paper in the form of graphs indicate their increase, which is most likely caused by industrial development, and therefore has an anthropogenic genesis. The carbon dioxide content in 2020 increased by about 140 ppm, while methane increased by about 1180 ppb compared to the average from the 11th to 18th centuries. These numbers show an increase in CO_2 and CH_4 concentrations in 2020 of 33% and 64% respectively. The global sea level is now about 24 cm higher than it was in the second half of the 19th century. Greenland has lost 5000 Gt of ice since the beginning of this century. On the basis of the area of the calved ice from the Jakobshavn Glacier calculated with the use of satellite data, we can see that Jakobshavn has lost 185 km^2 over the last 35 years, with as much as 148 km^2 occurring in the years 2000–2005.

The obvious way to deal with global warming is to reduce greenhouse gas emissions, which has become one of the priorities of world politics. The present study also aimed at investigating the applicability of satellite data in determining glacial zones with a case study of the Jakobshavn Glacier. As a result of the presented work, it can be concluded that free satellite data, acquired during the period of increased ablation (June to September), serves as an excellent source of data to achieve this goal. However, the correct interpretation of satellite images requires experience and appropriate digital processing and atmospheric correction for better reading of information from satellite images. It can be concluded that the easy availability of free satellite data facilitates analyses of snow cover changes over time. The results both pictorially and numerically make it possible to present the problem of global warming to an average citizen of the world in an excellent way.

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