PAGE21

THE LITTLE BOOK ON

Permafrost

SEVENTH FRAMEWORK PROGRAMME

About the book

INTRODUCTION

This e-learning material was created within the “PAGE21 – Permafrost in the Arctic and its Global Effects in the 21st Century“ project. The project is an EU Seventh Framework Programme funded large scale integrating collaborative project, aiming to understand the interactions between the global climate system and the frozen ground.

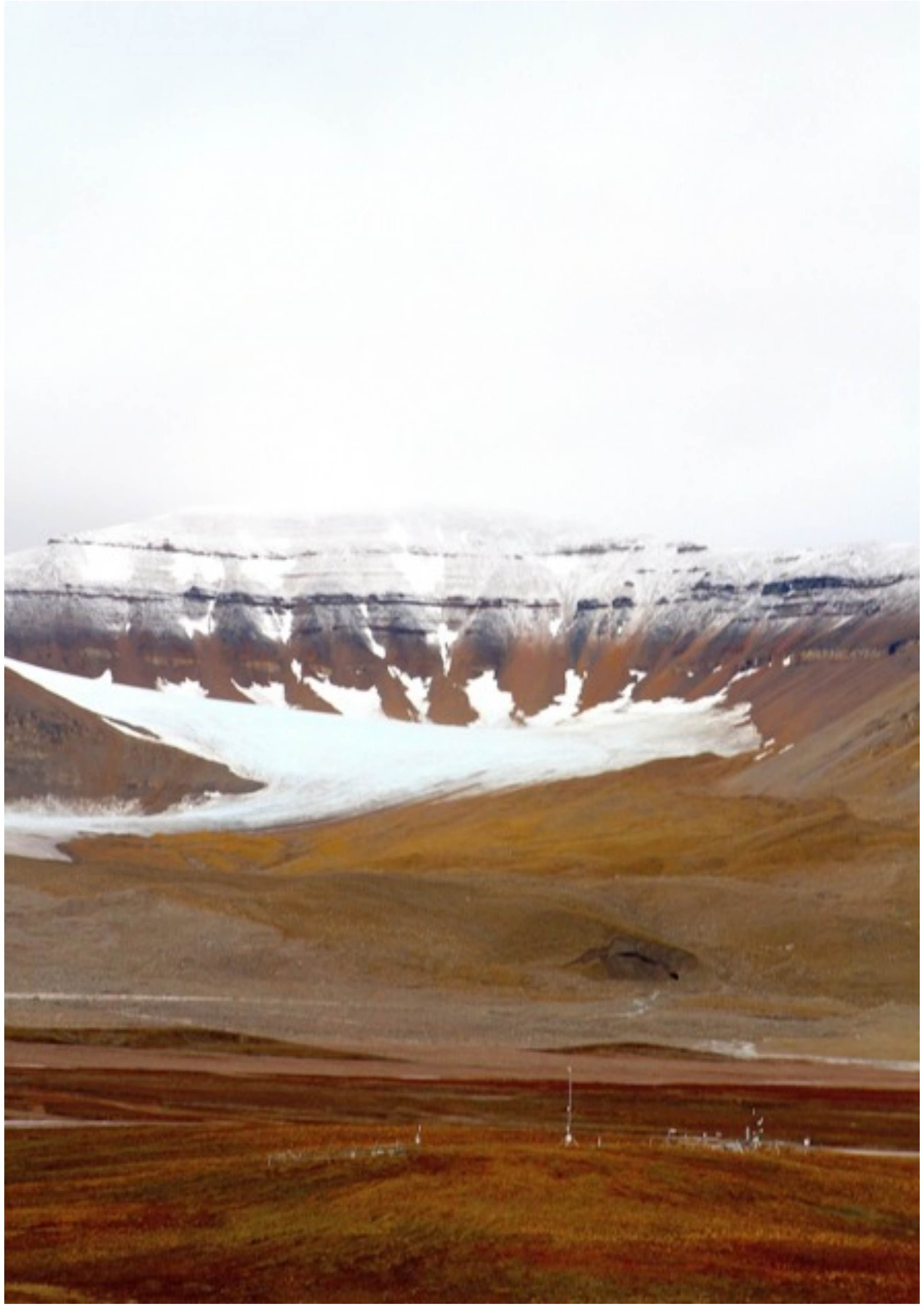
The multidisciplinary nature of the science and the wide range of countries covered in the PAGE21 project combine to provide a wealth of opportunities for disseminating information.

One of the tasks within the project was to create materials for education and training and that way ensure that the vast amount of knowledge entailed in the project consortium will be distributed to the widest possible audience for the benefit of community as a whole.

This e-learning material “Little book on Permafrost” was created by the PAGE21 participant Arctic Portal in Iceland with the support of the PAGE21 project office as well as the project coordination team at Alfred Wegener Institute, Potsdam, Germany.

The PAGE21 project e-learning material “Little book on permafrost” was developed in close cooperation with Prof. Dr. Kenji Yoshikawa from the Water and Environmental Research Center Institute of Northern Engineering at the University of Alaska Fairbanks.

The texts in this e-learning material are mostly based on Prof. Dr. Yoshikawa’s “Permafrost in Our Time” publication, an overview of an extensive permafrost temperature project that Prof. Dr. Yoshikawa has led in Alaskan schools, which came out in March 2013.

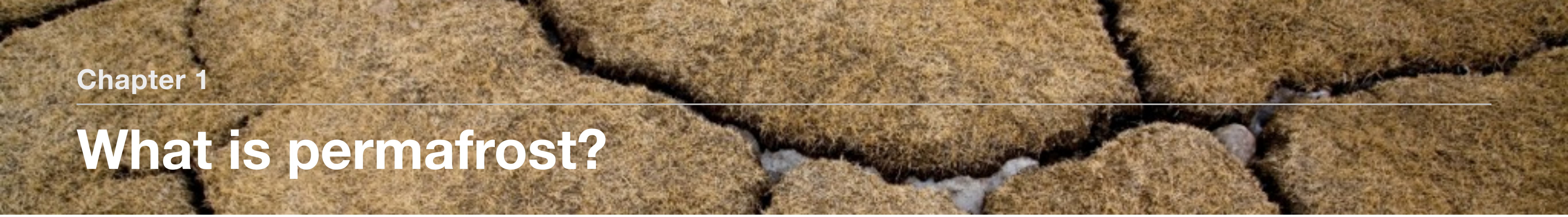


Permafrost lain area in Ny Alesund, northern part of Svalbard.
Photo: Hjalti Hreinsson

Chapter 1

What is Permafrost

This chapter introduces permafrost, explains how it is defined and familiarizes the reader with the major permafrost areas of the world.



Chapter 1

What is permafrost?

CHAPTER OVERVIEW

1. What is permafrost
2. Polygons
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4. Where can permafrost be found?

Permafrost is defined as ground that remains continuously at or below 0° degrees of Celsius for at least two consecutive years.

Permafrost is formed when the ground cools down in winter and produces a frozen layer below the surface that then remains frozen throughout the following summer, or longer.

Permafrost does not have to contain water or ice. As long as the temperature of the ground stays at or below freezing point year after year, it is still considered permafrost, even if the ground is completely dry. This is because permafrost is defined by temperature.

The active layer is the soil near the ground surface that thaws each summer, but freezes again during the winter. The ground temperature can fluctuate between 20 and 30°C between summer and winter.

Deep in the ground, however, soil temperature changes little from season to season. At 2–20m depth, depending on soil material, there is no seasonal change in temperature at all. It means that there is the same temperature all year around.

Deeper ground does not respond to heat coming from the atmosphere as quickly as the ground surface. In the middle of winter in February, ground surface is getting very cold, but that cold hasn't yet reached deeper underground. In April, though, it is the coldest time of the year at 1m depth. Sunshine is frequent in April in the North, and snow has melted in many areas. But only 1m below ground, it is the coldest time of the year and pipes to and from houses may freeze unless they're heated.

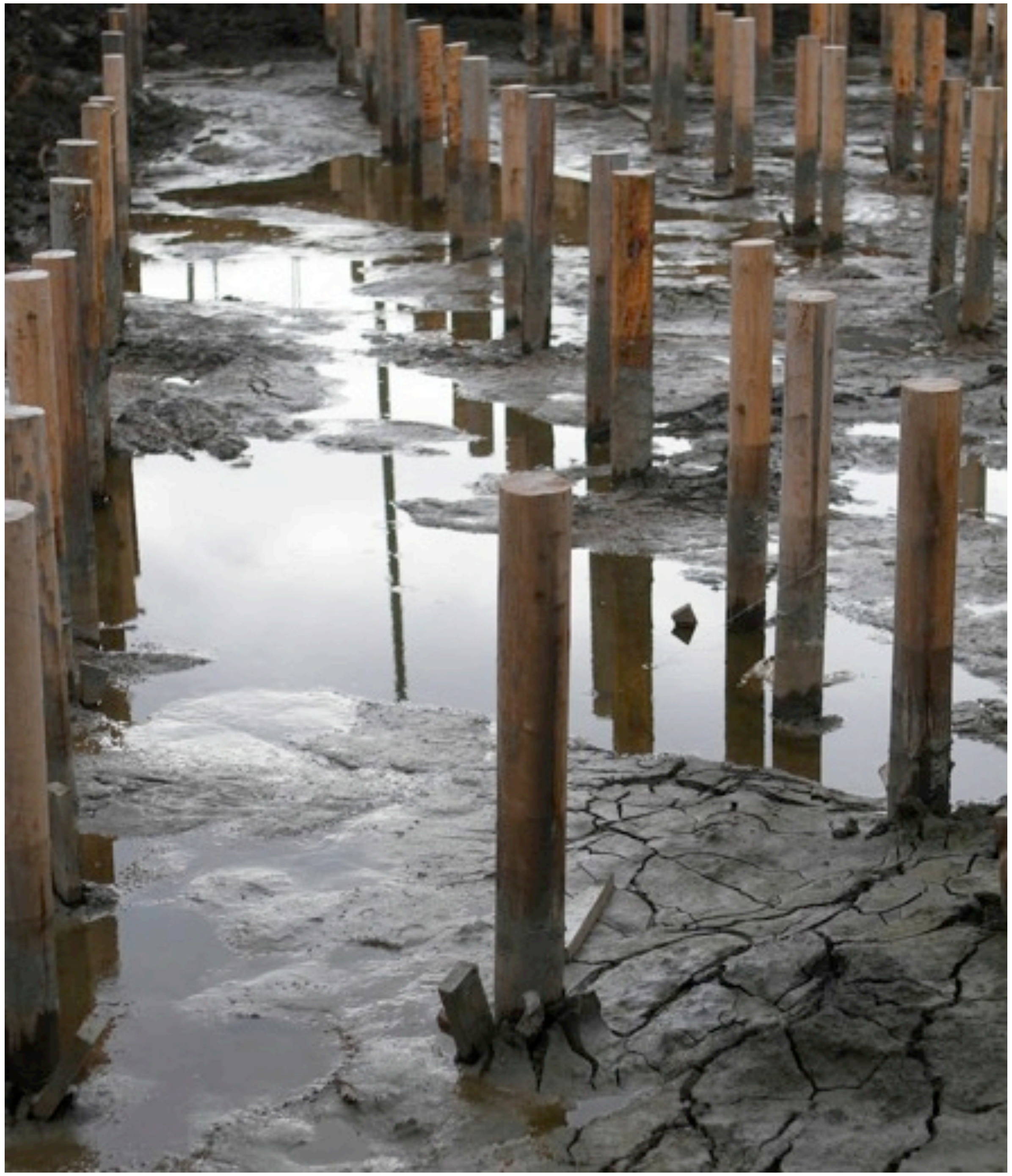
The thickness of permafrost depends on local climatic conditions, vegetation cover, soil type and soil moisture content. It is also impacted by the heat from the Earth's center. Permafrost thickness can vary a lot being anywhere from 1 meter to 1600 meters in depth. The deepest permafrost areas are in Siberia.

The earth´s core temperature is similar to the temperature of the sun's surface or approximately 5500°C. Earth´s average ground surface temperature, on the other hand, depends on where on earth it is measured.

Permafrost can be found where the average air temperature on the surface of the earth is around or below 0°C (32°F).

FACT!

Earth's average temperature is about 17°C, a temperature most humans feel comfortable in. The temperature range we live in is not wide compared to temperature variations in the universe. People can live in a range of only –50°C to 50°C (range 100°C), and that's with clothing for cold temperatures. For the naked condition, the temperature range we can live in is only 10° to 35°C.

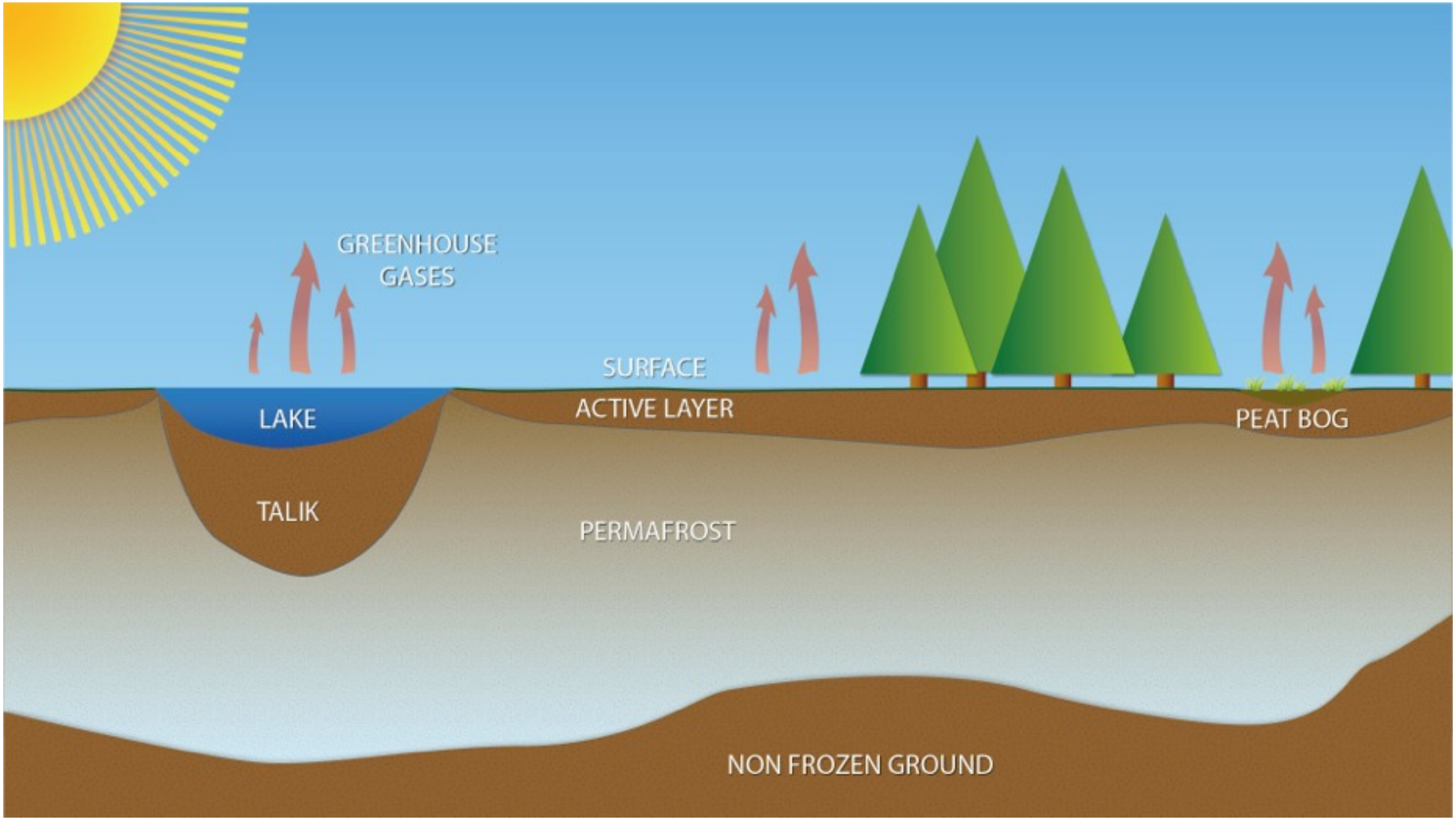


Houses in Svalbard are most often built on poles. Poles are run deep into the ground and houses built on top. It prevents flooding and sinking, resulted by permafrost. Storage can be used underneath the houses, commonly used for bikes etc.

Photo: Hjalti Hreinsson

Infograph: What is permafrost?

Illustration: Arctic Portal



Pipes in Svalbard are above ground because of permafrost. Bridges are for people and snowmobiles. Photo: Hjalti Hreinsson

Permafrost preserves bodies and therefore the cemetery in Longyerbyen has been for over 70 years. People who are ill are transferred to mainland Norway. Bodies of deceased people are also moved and not buried in Svalbard. Several graves fill the small cemetery, many of them miners who died in accidents and some who died as a result of the Spanish flu. The latest burial was conducted in the 1930´s. Photo: Hjalti Hreinsson

Houses in Longyearbyen, Svalbard. Poles are in front of the houses and storage areas can be seen underneath. Photo: Hjalti Hreinsson

Polygons

The polygons are formed due to the periodical freeze and thaw of the permafrost. When the climate gets colder in the fall, the active layer slowly starts to freeze.

In winter, during very low temperatures, the frozen soil fractures forming cracks on the ground. In spring when the ground starts to melt again the cracks fill with melting snow and water. This water stays in the cracks forming ice wedges in the permafrost when the soil again starts to freeze in the fall.

The ice wedges are only a few millimeters at first, but with time, when the active layer frequently freezes and thaws again the ice wedges get larger and form ice wedge polygons on the ground.

Both pictures show permafrost polygons. The picture on the right shows how polygons can also form underwater. *Photos: Julia Boike*

Infograph: Permafrost polygons *Illustration: Arctic Portal*

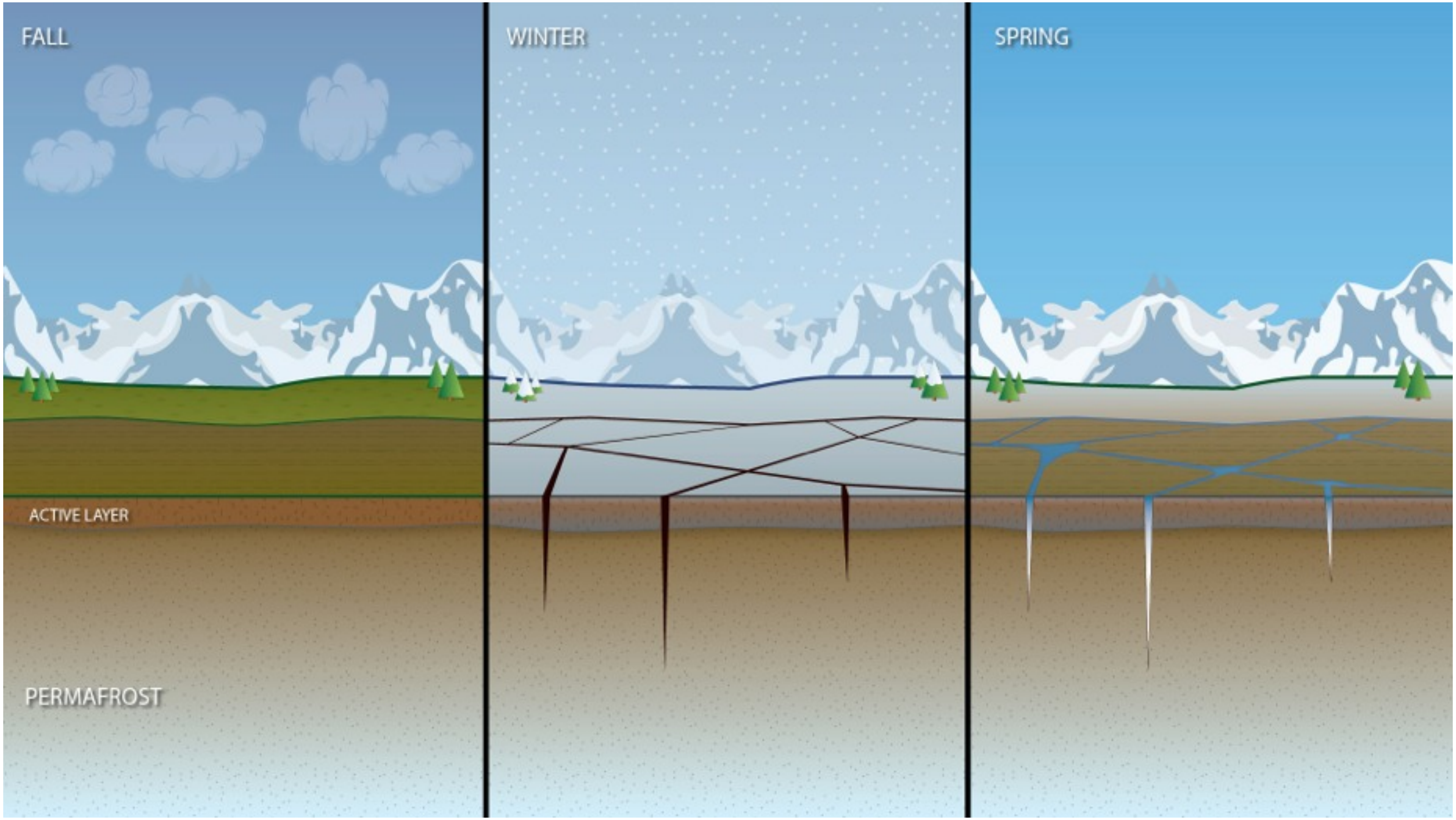
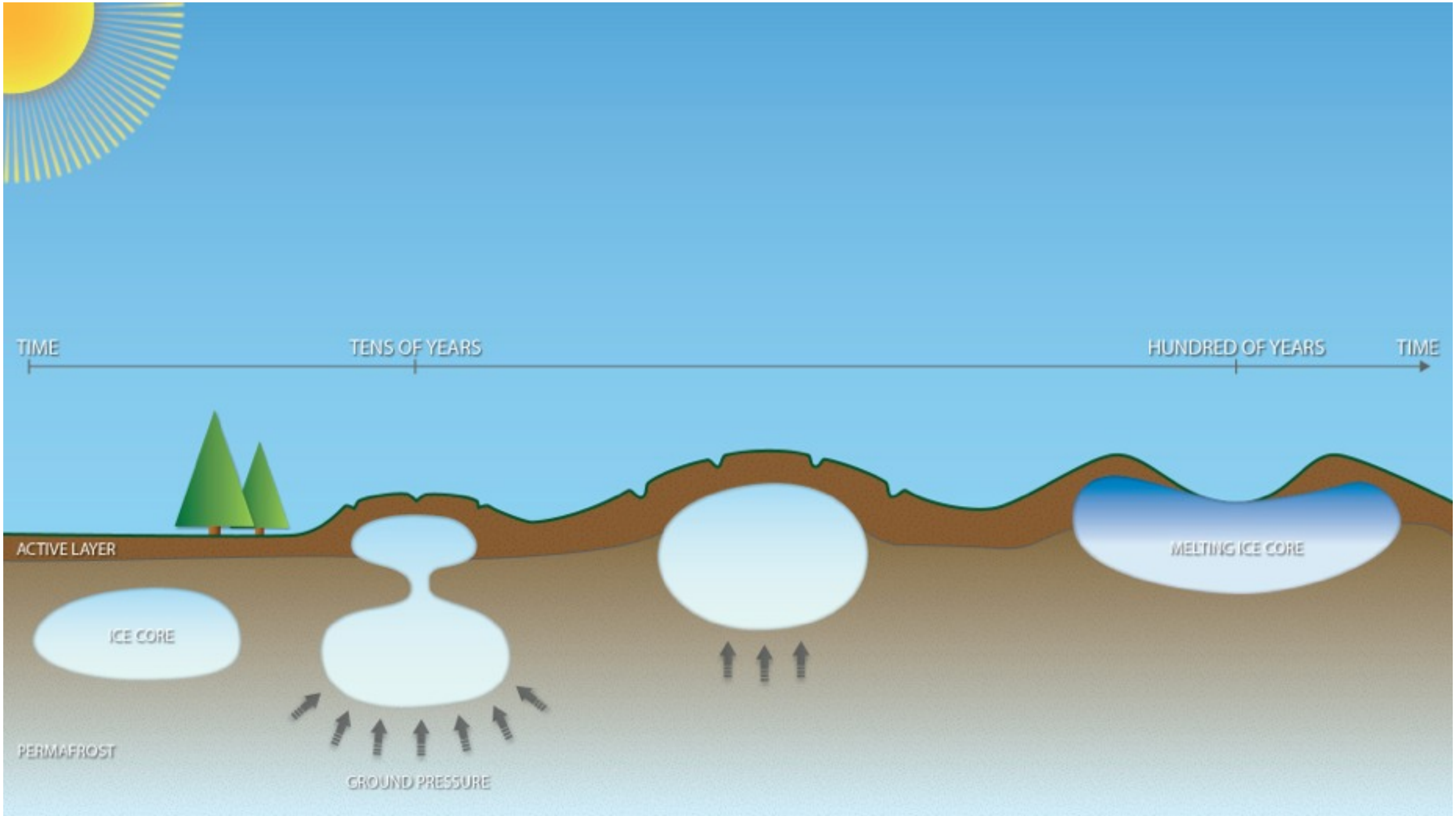


Illustration: Arctic Portal



Pingo is a small hill formed out of ice. When the pingo hill melts, the ground collapses and water runs into the centre forming a volcano crater-like pond.

Where can permafrost be found?

Arctic

Permafrost can be found in all regions in the Arctic.

Alaska

Permafrost is thickest in the northernmost part of Alaska, but it is found to some extent beneath nearly 85 percent of Alaska. On the Arctic coastal plain it extends as much as over 600m (2000 feet) below the surface and is found virtually everywhere.

Southward its thickness gradually decreases and it becomes more and more discontinuous, broken by taliks, pockets of unfrozen ground. Near Anchorage, permafrost is found only in isolated patches, and in Southeast Alaska it is found only high in the mountains.

Much of the permafrost in Alaska is tens of thousands of years old. River erosion and gold mining have revealed the remains of now-extinct animals from the last great ice age 100,000 to 10,000 years ago, when animals such as woolly mammoths, mastodons, lions, and saber-toothed cats roamed what is now Alaska.

In Alaska, permafrost observatories, equipped with boreholes, were established in the 1970s and 1980s along the Trans-Alaskan Pipeline as well as at other locations in Alaska by the Geophysical

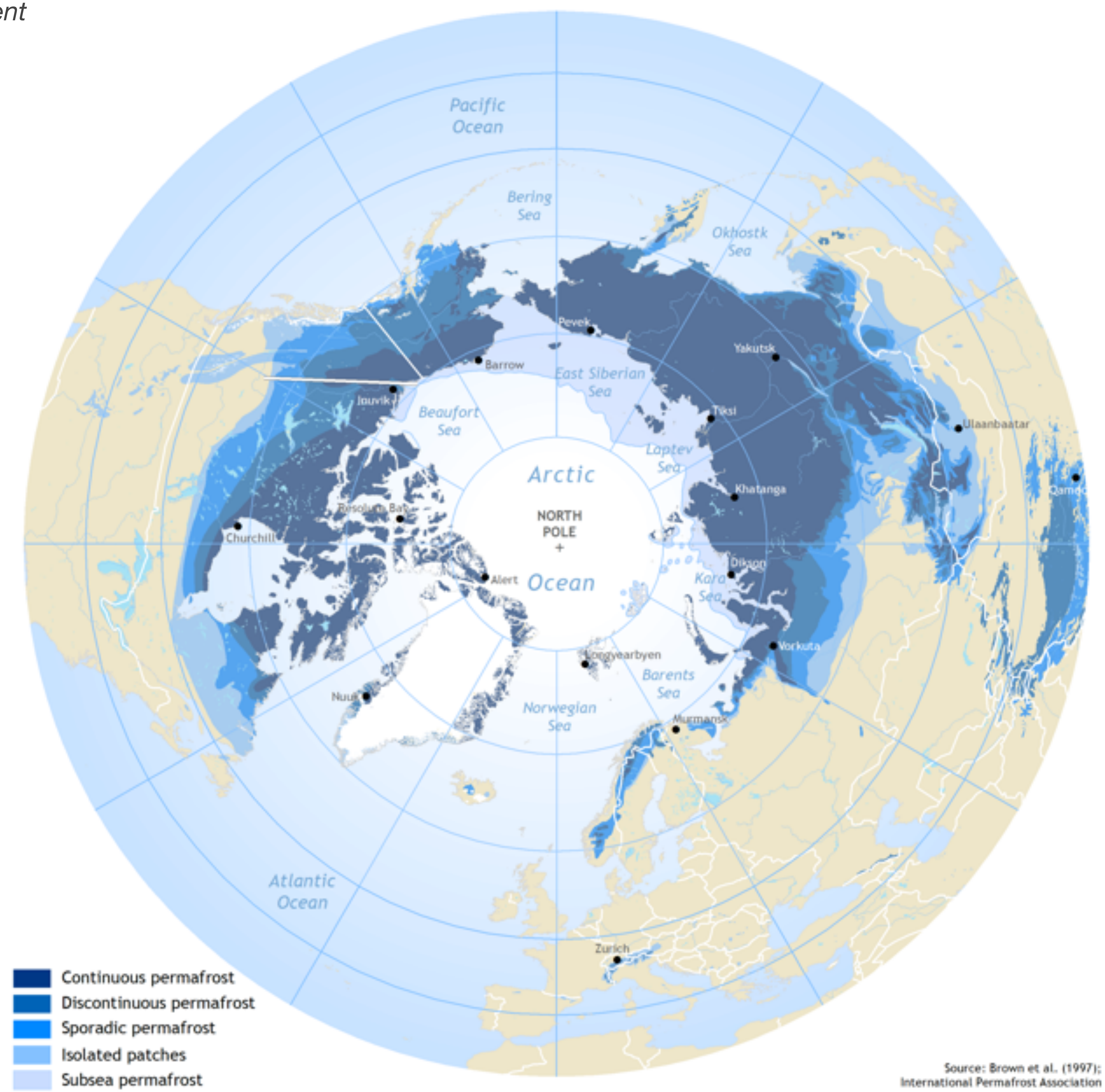
Permafrost ground. *Photo: GettyImages*

Institute of University of Alaska Fairbanks. Depths of these boreholes are typically 60 to 80m, and measurements are usually taken annually. Since the early 1990´s, permafrost temperatures in Alaska have changed noticeably. Generally, the increases in permafrost temperature are more profound at coastal Arctic sites (from 1.5 to 3.0°C) and less profound in interior Alaska (from 0.5 to 1.5°C).

Canada

The Canadian Arctic Archipelago, located in the northern extremity of North America, covers approximately 1,424,500 km2 (550,000 sq.mi). It consists of 36.563 islands, and covers a large

Map: Permafrost Extent



Source: Brown et al. (1997);
International Permafrost Association

part of Northern Canada – most of Nunavut and part of the Northwest Territories. It is one of the coldest permafrost temperature regions in Northern Hemisphere, going down to -14°C.

Retrogressive thaw slumps, which develop due to the thawing of ice-rich permafrost on slopes, are commonly seen at Western part of Canadian Arctic. These huge thaw slumps trigger massive sediment export from the permafrost and a lot of suspended solid discharges to the ocean.

Siberia – Russia

Siberia contributes the most to the world's permafrost proportion. The thickest permafrost in the world is found in Siberia (over 1000m). Subsea permafrost is also widely present in the offshore of the Siberian Arctic Coast.

Northern Siberian coastal Islands (Novosibirsk Islands) are one of the coldest permafrost areas in Siberia. Interestingly, Oymyakon, one of the coldest places in Northern hemisphere with -72ºC record minimum temperature, does not have the coldest permafrost temperature, because of very hot summer temperature.

Permafrost research site in Ny Alesund, Svalbard. *Photo: Hjalti Hreinsson*

Scandinavia

Permafrost can be found in most places in Svalbard and its temperature ranges from -2 to -6°C. The temperature depends on local climate, snow cover and vegetation conditions at the ground surface as well as on the soil moisture and thermal properties of the subsurface.

In 2008, a borehole was drilled close to Longyearbyen school as a part of the International Polar Year TSP Norway project with the purpose of monitoring the temperature in the permafrost.

The hole was drilled about 100m south of the school to a depth of nearly 10m. The site has a thin snow cover in wintertime and there is no vegetation and no organic horizon at the site.

Measurements from the borehole show that while the temperature at the ground surface ranged from 20°C during summer to -25°C during winter, the permafrost temperature stayed at -3 to -4°C at 9m depth. The active layer measured about 2.5m thick.

Beside Svalbard, permafrost can be found in northern Scandinavia and Iceland. Palsa peat land is common in northern Finland, where ice lenses accumulate to plateau or mound shaped landforms. Thawing of these ice lenses has great impact on the infrastructure in the area.

Mountain in Greenland *Photo: GettyImages*

Greenland

Greenland (Kalaallit Nunaat) is occupied by the biggest ice cap in the Northern Hemisphere. Permafrost in Greenland, in open terrains, is located at the edge of the ice cap as well as in fjords. It cannot be found in southern part of Greenland, but is present north of Nuuk in the west coast and north of Tasiilaq in the east coast.

Permafrost temperature in Western Greenland is warm, mostly above -3°C or warmer. Also many open system pingos are around the Disko Bay area and the Nugsuaq Peninsula.

Kangerlussuaq is one of the oldest permafrost monitoring sites in Greenland, because of the presence of the US air force base. Several boreholes are connected with a computer system and monitored regularly.

South America

Andes is the longest continental mountain range in the world. The range is about 7000km long the average height being around 4000m. The Andes extend from north to south through seven South American countries: Venezuela, Colombia, Ecuador, Peru, Bolivia, Chile and Argentina.

The highest peak, Mount Aconcagua, rises to an elevation of about 6962m above sea level. The peak of Chimborazo in the Ecuadorean Andes is farthest from Earth's centre compared to any other location on Earth's surface, due to the equatorial bulge resulting from Earth's rotation. The world's highest volcanoes are in the Andes, including Ojos del Salado on the Chile-Argentina border, which rises to 6893m. Over fifty other Andean volcanoes also rise above 6000m.

Permafrost is commonly seen above 5500m in tropical regions in Peru and Bolivia, and lower elevation in Argentine and Chile. Volcanic activity is one of the important parameters for the presence or absence of the permafrost, because most of the high mountains in Andes are volcanoes. With higher heat flow, the ground stays warm (sometimes above 10°C) in spite of the cold annual mean air temperature.

Surface albedo, the proportion of the incident light or radiation reflected by a surface, is also important in tropical mountains. The solar rays at tropical regions are much stronger than at the polar

The Andes mountain range. *Illustration: Arctic Portal*

regions. Darker surface absorbs a lot of heat while white surface indicates usually the presence of permafrost.

Africa

There are three mountains in Africa that have glaciers; Mount Kilimanjaro (5895m), Mount Kenya (5199m) and Ruwenzori (5109m).

All these mountains are close to each other around the Lake Victoria near equator. The presence of the glaciers is more likely due to the higher precipitation rather than temperature factors.

Mount Kilimanjaro is one of the most famous mountains in the world. Also its unique mountain shape and location along the equator are attractive features to many people.

However, the presence of permafrost at the Mt Kilimanjaro is almost unknown, because the mountain summit has never been drilled properly. Attempts searching for permafrost were though conducted in 2009 giving better understanding on thermal state of the ground of the mountain

Kilimanjaro is a large stratovolcano. Two of its three peaks, Mawenzi and Shira, are extinct while Kibo (the highest peak) is dormant and could erupt again.

The last major eruption in Kilimanjaro has been dated to between 150,000 and 200,000 years ago.

Africa. *Illustration: Arctic Portal*

Although it is dormant, Kibo has fumaroles that emit gas in the crater. Several collapses and landslides have occurred on Kibo in the past, one creating the area known as the Western Breach.

One of the temperature monitoring sites at Kilimanjaro showed 3m below ground surface temperature of 0.03°C all year around.

This means simply that thawing/freezing temperature is controlled by latent heat. Kilimanjaro does not have clear seasonal changes, which means that there are almost no seasonal temperature fluctuations. However, it has big daily temperature fluctuations of up to 40 to 50°C between day and night making sunshine a controlling factor.

Snow is also very important for the thermal state of Kilimanjaro as well as other tropical mountains, since solar radiation is very strong. The ground surface temperature can be over 40°C because of the sun even though the air temperature stays below 0°C.

Central Asia

Tibet

The Tibetan Plateau is surrounded by massive mountain ranges. The plateau is bordered in south by the Himalayan range, in the north by the Kunlun Mountains which separates it from the Tarim Basin, and in the northeast by the Qilian Mountains which separates the plateau from the Hexi Corridor and Gobi Desert.

The Tibetan Plateau is bounded in the north by a broad escarpment where the altitude drops from around 5,000m to 1,500m in less than 150km.

From the Himalayas. *Photo: GettyImages*

The plateau is a high-altitude arid steppe interspersed with mountain ranges and large brackish lakes. Annual precipitation ranges from 100 to 300 millimeters and falls mainly as hailstorms. The southern and eastern edges of the steppe have grasslands which can sustainably support populations of nomadic herdsmen, although frost occurs for six months of the year.

Permafrost occurs over extensive parts of the plateau. Proceeding to the north and northwest, the plateau becomes progressively higher, colder and drier, until reaching the remote Changthang region in the northwestern part of the plateau.

Mashan is located east end of this region and has permafrost higher than 3500 m above sea level. Permafrost in Tienshan Mountain is also well studied.

The lower limit of the permafrost is 4000m at South facing slopes, and 3500m at north facing slopes. Strong solar radiation creates the asymmetric environments.

Tibetan Plateau has widely distributed presence of the lower latitude permafrost. Permafrost temperature is warmer than -1°C most of the plateau and about 100m thick.

The permafrost area lies not only within China, but is also located within India, Nepal, Afghanistan, Kirgizstan, and Kazakhstan (in the Tientian Mountains).

From the Himalayas. *Photo: GettyImages*

Southern Siberia

Permafrost distribution occupies almost two thirds of Mongolia, predominantly in the Khentei, Hovsgol, Khangai and Altai mountains and surrounding areas. The territory is characterized by mountain and arid-land permafrost, sporadic to continuous in its extent, and occupies the southern fringe of the Siberian permafrost zones. Most of the permafrost is at temperatures close to 0°C, and thus, thermally unstable.

In the continuous and discontinuous permafrost areas, taliks are found on steep south-facing slopes, under large river channels and deep lake bottoms, and along tectonic fractures with hydrothermal activity.

In sporadic and isolated permafrost areas, frozen ground is found only on north-facing slopes and in fine-grained and moist deposits.

Perennial frost mounds are widespread in both large and small intermountain lake basins in Mongolia. They are found in areas where permafrost is geographically discontinuous, as well as those underlain continuously by permafrost.

Permafrost monitoring shows that permafrost in Mongolia is degrading at various places, but the rates are depending on the local natural conditions.

Permafrost, especially sporadic and isolated, is very sensitive to climate change and human activities. Besides climate warming, factors of permafrost degradation are deforestation in the taiga and desertification in the steppe zones of Mongolia.

Permafrost monitoring in this areas is, therefore, of both scientific and practical importance.

From the Himalayas. *Photo: GettyImages*

Pacific

Japan

Permafrost is present in the mountain regions of Hokkaido and Honshu islands. Mount Fuji (3776m) is the southern limit of permafrost in the Western Pacific. Several high tropical mountains such as Yushan (3952m) in Taiwan, Mount Kinabaru (4095m) in Malaysia, or Puncak Jaya or Carstensz Pyramid (4884m) in Indonesia are located at lower latitudes, but likely are not high enough to develop permafrost in current climatic conditions.

Mt. Fuji, located on Honshu Island, is the highest mountain in Japan. It is an active stratovolcano that last erupted in 1707–08. Mt. Fuji lies about 100km (62 mi) southwest of Tokyo, and can be seen from there on a clear day.

Mount Fuji's exceptionally symmetrical cone, which is snow-capped several months of the year and well-known symbol of Japan, is frequently depicted in art and photographs, and is visited by sightseers and climbers. Permafrost is present at most of the summit area as low as 3000 m at north-facing slopes. A borehole temperature shows -3°C at 10m depth near the summit.

As an active volcano, Mount Fuji's geothermal heat flow is higher, and the permafrost is considered recent, or since the last eruption (1708). This newly developed, young permafrost is a unique phenomenon. Surficial geology is also important for the presence of permafrost. The ice-rich ash layer or tuff would provide strong thermal resistance and ideal material for stable permafrost in the mountain.

Map of Japan and the peaks Fuji (3776m) and Daisetsu (2290m).

Illustration: Arctic Portal

Daisetsu (also spelled Taisetsu) Volcano is a group of 8 stratovolcanoes, lava domes, and a small 2 km wide caldera in central Hokkaido. The lower limit of permafrost there is above 1650 m a.s.l. depending on winter snow conditions and the surficial geology (sand and gravel).

Hokkaidaira borehole shows that the active layer is between 1 and 1.5m, and the permafrost temperature is around -1°C at 4m depth. In addition to the mountain area, some of the lower area of Hokkaido Island has permafrost.

Permafrost at the Oketo site is in critical condition, as it is thawing following warm winters. Wide areas of eastern Hokkaido Island freeze severely during winter months. Seasonal frost depth sometimes reaches 1 m, which is deeper than the southern part of Alaska.

Presently, dozens of schools in Japan have frost tubes and ground temperature data loggers. Japanese students measure frost depth in their school yards usually from November to March.

Map of Hawaii and the peaks Mauna Kea (4205m) and Mauna Loa (4169m). *Illustration: Arctic Portal*

Hawaii

Many people find it hard to believe that there is permafrost in the tropical Hawaiian Islands, but due to altitude, there is permafrost on Hawai'i, the big island. If we go to higher latitudes (toward the poles), temperatures get colder. It's the same with altitude; the higher we climb, the colder the temperatures get, both in air and on the ground.

Mauna Kea is at the critical height for developing permafrost. In late 1969, marine scientist, Dr. Alfred Woodcock, was the first person to discover and study the permafrost there. He found that, at the summit, the average air temperature was well above freezing, but at the permafrost site, on the north-facing slope of the summit crater at 4140m, it was much lower.

Mauna Kea was glaciated during the Ice Age. Moraines and erratics (isolated boulders) can be seen there today. These relict features reveal the existence of a past glacier (at 3000–3500m altitude).

The rate of temperature decrease with elevation, called the lapse rate, is constant at about 6.5°C/1000m below about 1250m, and 4°C/1000m at higher elevations. In this case, permafrost should be absent below an altitude of about 5000m, but the permafrost at Mauna Kea is affected by local microclimate systems. This is a good example of tropical mountain permafrost distribution, and useful for Martian permafrost study.

Permafrost at Mauna Kea is located on the lower north-facing slope of the summit crater. There is no permafrost at the crater floor. The location of this permafrost indicates the importance of reduced sunlight on permafrost survival.

The inter-annual variation of temperature in a tropical alpine climate is typically small (about 4°C). Zero annual amplitude depth is about 5m below ground and about -0.1°C. The base of the permafrost is 10.5m.

Permafrost may be present also on Mauna Loa, but this is not confirmed yet. Mauna Loa means “long mountain,” with elevation of 4169m, only 38m lower than Mauna Kea.

The NOAA Mauna Loa Observatory (MLO) is located at 3400m on the northern slope of the mountain. The MLO monitors global atmosphere, including greenhouse gases and carbon dioxide.

Mauna Kea in Hawaii.

Photo: Wikipedia commons

Antarctica

Antarctica is the coldest of Earth's continents. The coldest natural temperature ever recorded on Earth was –89.2 °C at the Russian Vostok Station in Antarctica on 21 July 1983. Antarctica is a frozen desert with little precipitation; the South Pole itself receives less than 100 mm of rain per year, on average.

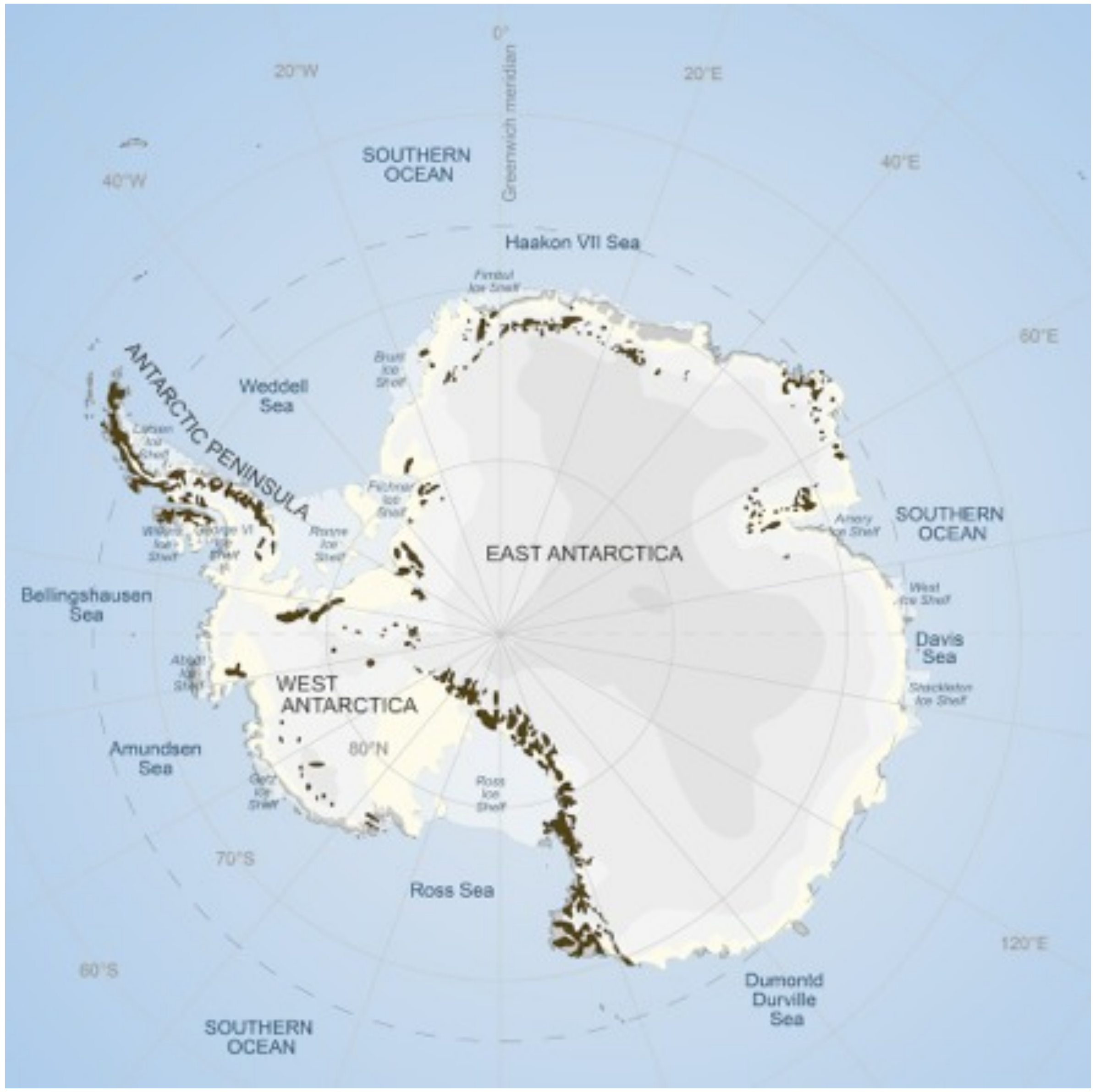
Permafrost is present only on 0.36% (49.800 km2) of the Antarctic region, beneath virtually all ice-free terrain, except at the lowest elevations of the maritime Antarctic and sub- Antarctic islands.

Antarctica is colder than the Arctic for three reasons. First, much of the continent is more than 3km above sea level, and temperature decreases with elevation. Second, the Arctic Ocean covers the north polar region.

Third, earth is at aphelion in July (i.e., the earth is furthest from the sun in Antarctic winter), and the earth is at perihelion in January (i.e. the earth is closest to the sun in Antarctic summer.

The orbital distance contributes to a colder Antarctic winter (and a warmer Antarctic summer), but the first two reasons have though more impact.

Freeze-thaw cycles are less frequent in Antarctica although commonly seen on rock physical weathering. At Independence Hill in Ellsworth Mountains, inland Antarctica, rock surface temperature exceeded 0°C about 47 times, while mean annual



Permafrost is present on 0.36% of the Antarctic

Illustration: Arctic Portal

rock surface temperature was -21°C during 1992-93 expedition time.

Permafrost temperature is also the coldest (colder than -20°C) compared with other Antarctic coastal stations.

The Moon

There are some indications that permafrost could also be found on the moon.

On July 26, 1971, during the Apollo 15 lunar landing mission, two thermal-property boreholes were drilled at 26°4’54” north latitude, 3°39’30” east longitude, at the base of the Apennine Mountains. The Apennines rise more than 4572m along the southeastern edge of Mare Imbrium (Sea of Rains).

The final Apollo mission, Apollo 17 in 1972, landed at Taurus-Littrow, a lunar valley named after nearby Littrow crater and the Taurus Mountains, on the southeastern rim of the Serenitatis basin. A borehole was drilled to 2.9 m.

During the Apollo 15 and 17 missions, temperature sensors (platinum resister) were installed in 2–3 m boreholes at 20–26° north latitude.

Geologist-Astronaut Harrison Schmitt worked next to a huge, split boulder at geology Station 6 on the sloping base of North Massif during the third Apollo 17 extravehicular activity. *Photo: NASA/Commander Eugene A. Cernan*

Mars

Mars is the fourth planet from the sun, about half (53 percent) the size of Earth. Permafrost is widespread throughout most of the planet. Several kilometers thick permafrost is expected to be found in Polar regions of Mars.

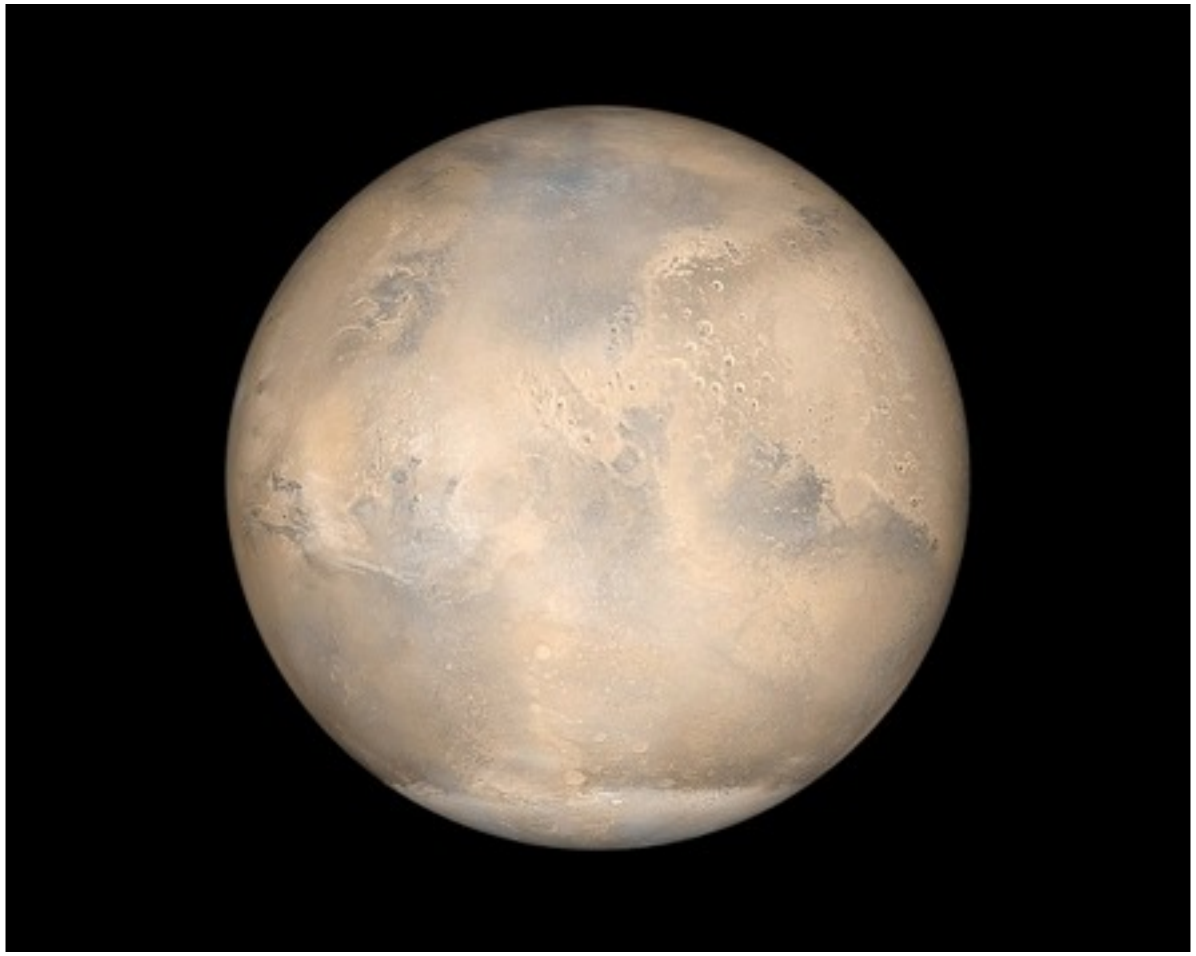
Ground temperatures and air temperatures generally differ, perhaps because the air in Mars is much thinner than the air in Earth (about 140 times thinner).

The surface of the planet absorbs much of the solar energy, where the atmosphere lets the sunlight pass through it. This means that daytime high temperatures are usually higher for the ground than the air.

An extreme example might be walking on the sidewalk or a beach, barefoot on a hot summer day. The air is hot, but the ground is much hotter and you could even burn your feet. Similarly the ground can cool at night, more efficiently than can the air, by infrared radiation.

On Earth this can result in a dew or frost forming on the ground where warmer wet air contacts the colder ground (much like water droplets forming on the outside of a glass of ice water).

As for seasons, Mars experiences seasons like the Earth because of a similar tilt in its spin axis. The Martian year, however, is about 687 Earth days long.



Mars. *Photo: NASA*

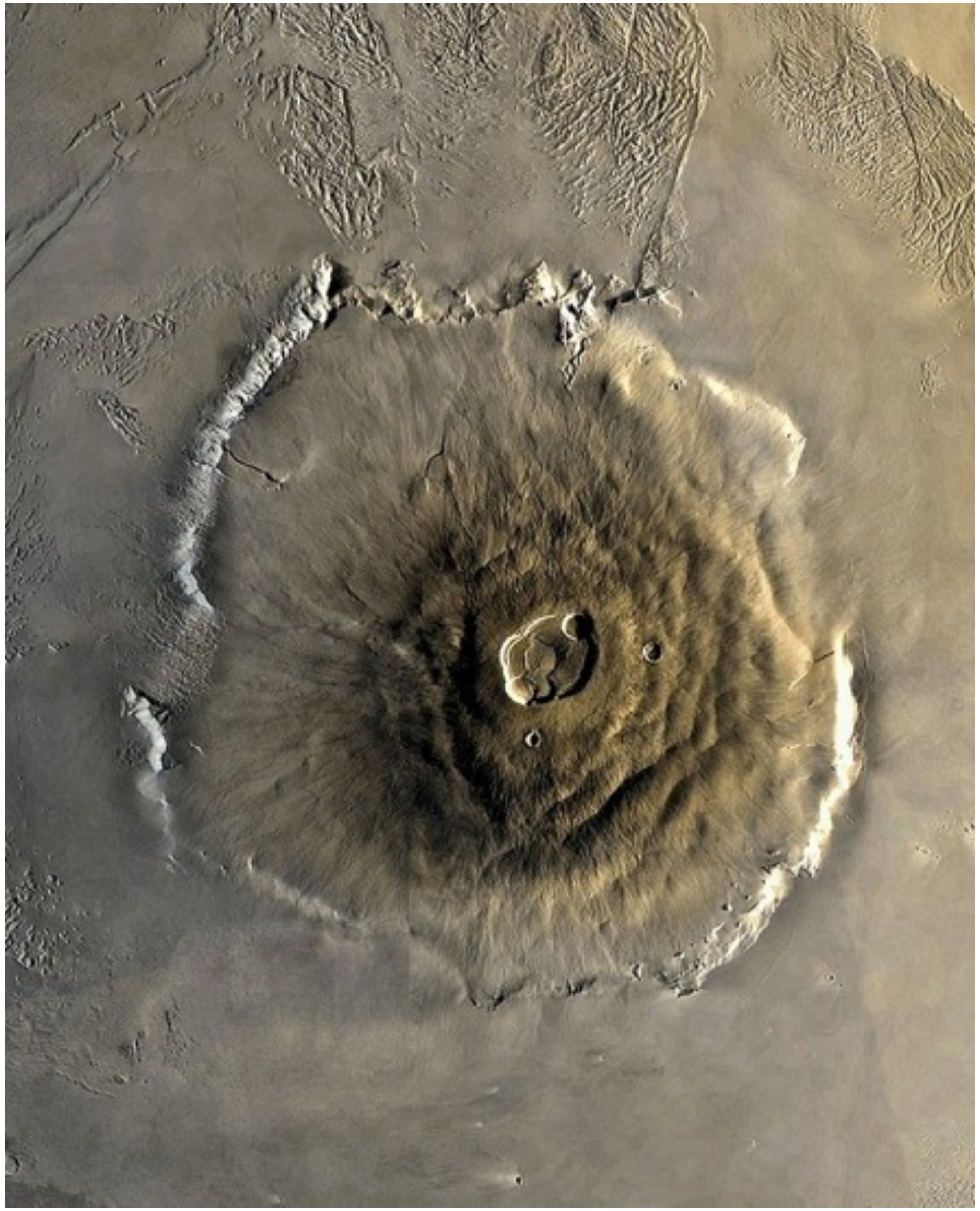
Mars is farther from the Sun than the Earth and thus receives less light from the Sun, which makes it colder. The average surface temperature on Mars is about -53°C.

During the middle of the day at the equator, however, the temperature of the surface can rise to above the melting point of ice (0°C); it occasionally will get as warm as a pleasant spring day on Earth.

Of course, during the long polar night, when the Sun doesn't rise for half a year, the temperature can drop to as low as -133°C.

Variety of polygonal landscapes is found on Mars, especially in polar regions. Some of the polygons must be frost contraction polygons similar to the ice wedge polygons in Arctic regions on Earth.

Also, unknown directional polygonal ground has been discovered in Utopia Planetia. These polygons are unlike ice wedge polygons on earth, but are considered to be related in geological structure.



Color mosaic of Olympus Mons on Mars. *Photo: NASA*

Chapter 2

Permafrost and Climate Change

Permafrost is influenced by climate change. Global warming can lead to permafrost thaw which impacts both the climate system with the release of greenhouse gases and the infrastructure, which has been built on permanently frozen ground.

Chapter 2

Climate change and permafrost

CHAPTER OVERVIEW

1. What is climate change?
2. Permafrost thaw

During the last ice age, Earth was colder than today. Sea level was also much lower than today, because so much of Earth's water was on land, frozen in glaciers. Siberia and Alaska were connected by the Bering Land Bridge and people living in this area, Beringia, hunted the largest ice-age mammal, the mammoth.

Since we emerged from the last ice age around 11,000 years ago, the Earth's climate has remained relatively stable, with global temperatures averaging at about 14°C. However, in the last century our climate has started to change rapidly.

This isn't thought to be just a temporary blip in the system; the evidence points to a long-term change in our climate which is happening at an unusual rate.

But how can we tell if these changes are natural or whether they are down to us?

What is climate change?

The Earth's climate has changed on many timescales in response to natural factors. On long timescales, such as tens of thousands of years, we see the Earth move in and out of ice ages.

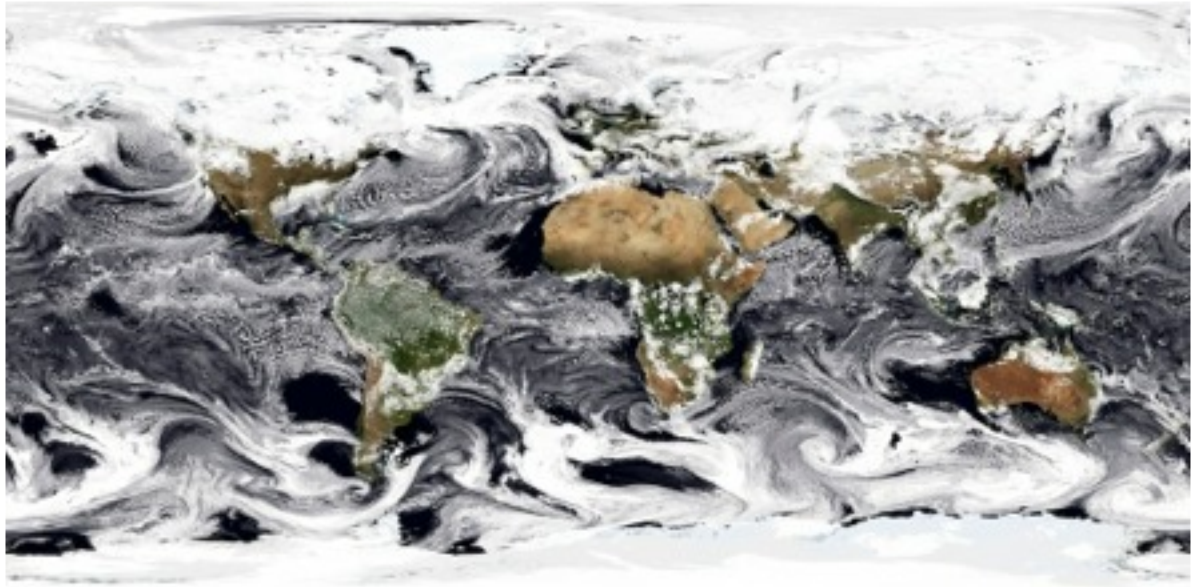
At the other extreme, El Ninos come and go every few years, temporarily raising the Earth's temperature. So, what aspects of our climate are changing and what is causing these changes?

Since we emerged from the last ice age around 11,000 years ago, the Earth's climate has remained relatively stable, with global temperatures averaging at about 14°C. However, in the last century our climate has started to change rapidly.

This isn't thought to be just a temporary blip in the system; the evidence points to a long-term change in our climate which is happening at an unusual rate. But how can we tell if these changes are natural or whether they are down to us?

There are many factors that can cause a warming of our climate; for example, more energy from the sun, large natural events such as El Nino or an increased greenhouse effect.

Scientists have ruled out the sun and natural variations in our climate as the major causes of the recent warming.



The climate system changes regularly, but changes are happening faster now then ever. *Photo: GettyImages*

There is overwhelming evidence that most of this warming we've seen is due to increased amounts of greenhouse gases in the atmosphere.

Greenhouse gases, such as water vapour, carbon dioxide and methane, occur naturally in the atmosphere. But human activities have directly increased the amount of carbon dioxide, methane and some other greenhouse gases.

These increases can be through the burning of fossil fuels such as oil and coal, and changes in land use such as chopping down forests for cattle grazing.

Carbon dioxide and methane are both important greenhouse gases which have the greatest effect on our changing climate.

Methane has a stronger greenhouse effect, but there is less of it and it only remains in the atmosphere for about a decade.

Carbon dioxide on the other hand is much more abundant in the atmosphere and lasts for about 100 years or more, having a greater cumulative affect on our climate.

The amount of carbon dioxide in our atmosphere has increased by 38% since the industrial revolution and because it stays for such a long time in our atmosphere, as we emit more it continues to build up.

The world has warmed by three-quarters of a degree in the last century. On top of this we have seen changes in extremes of weather events, such as heatwaves and heavy rainfall.

There is a natural carbon cycle in our climate. Carbon dioxide enters the atmosphere from a variety of sources, from the oceans, land and vegetation, from animals breathing or volcanoes erupting. They are sources of carbon dioxide.

This in turn is absorbed by things like trees and plants, especially as they grow, by rocks and by the oceans.

They are sinks of carbon dioxide. This cycle has been delicately balanced for thousands of years.

Photo: GettyImages

However, the increases in the level of carbon dioxide in the atmosphere can not only be explained by these natural phenomena.

The current changes are very unusual and can not be explained simply as part of any natural cycle, such as El Nino and La Nina, which cause the warming and

cooling of the tropical Pacific Ocean, which affects world temperature. Natural cycles can lead to periods with little or no warming and other periods with rapid warming.

However, what is important is to look at the longer term trends in temperature, which are rising, and which scientists believe is almost certainly caused by human activity.

When studying climate change, scientists draw their evidence from many sources. Are humans contributing to the warming we are observing? Or could it be natural causes and changes to the climate?

Scientists, such as those at the Met Office Hadley Centre, are continuing to look at all the possible effects, both man-made and natural. However, it is widely understood that our emissions of greenhouse gases are causing changes to our climate.

Melting ice in the Arctic has worldwide effects. *Photo:GettyImages*

Permafrost Thaw

Most of the permafrost existing today was formed during the last ice age, from approximately 110,000 to 10,000 years ago. Thicker permafrost was formed in areas that were not glaciated because of the ground surface was exposed to cold air instead of been covered by glacier.

Because of this warming climate, permafrost is now expected to thaw. This thawing can have severe consequences for infrastructure in permafrost areas but most importantly, it will allow previously frozen carbon to be transformed by microbes into carbon dioxide or methane.

Scientists have established that previously unsuspected amounts of carbon and nitrogen could be released in to the atmosphere, possibly accelerating global warming even more.

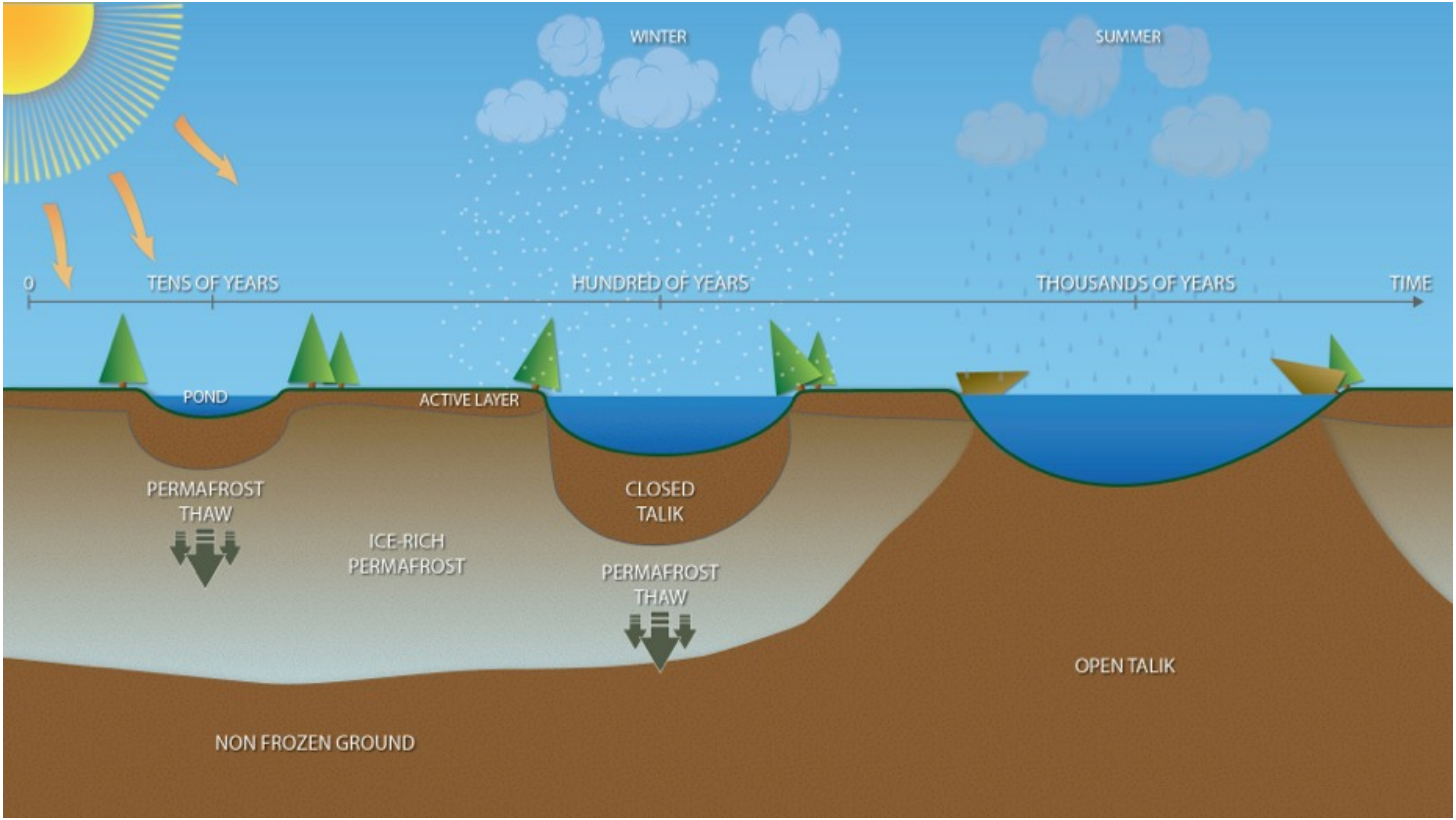
Fact!

”Permafrost melting” is incorrect terminology that results from a misinterpretation of the physical process of permafrost degradation. “Melting” describes a physical phase change during a temperature increase when a solid substance is transformed into a liquid state. Hence, the term “permafrost melting” suggests the transition of solidly frozen permafrost terrain into a liquid. Instead, the term permafrost thaw should be used.

This picture is taken in Siberia of a former Stalin camp. The remnants are collapsing due to permafrost thaw.

Photo: Peter Prokosch

Illustration: Arctic Portal



Chapter 3

Permafrost Research

Permafrost research is conducted throughout the world. There are several methods to research the ground and estimate the features affecting permafrost. Here are introduced some of the main research methods.

Chapter 3

Permafrost research

CHAPTER OVERVIEW

1. **Permafrost coring**
2. **Atmospheric measurements**
3. **Remote sensing**
4. **Other measurements**

Permafrost research is conducted throughout the world. There are several methods to research the ground and estimate the features affecting permafrost.

Here are introduced some of the main research methods.

Permafrost coring

The permafrost landscape is temperature-sensitive like ice-cream and manifold like the pieces of a puzzle. Beside weather, plant cover, soil type and snow cover, also the composition of the permafrost can vary considerably from site to site.

If we want to forecast (or model) what happens to the permafrost landscape when climate changes we need to better understanding this heterogeneity.

One approach is permafrost coring and core analysis.

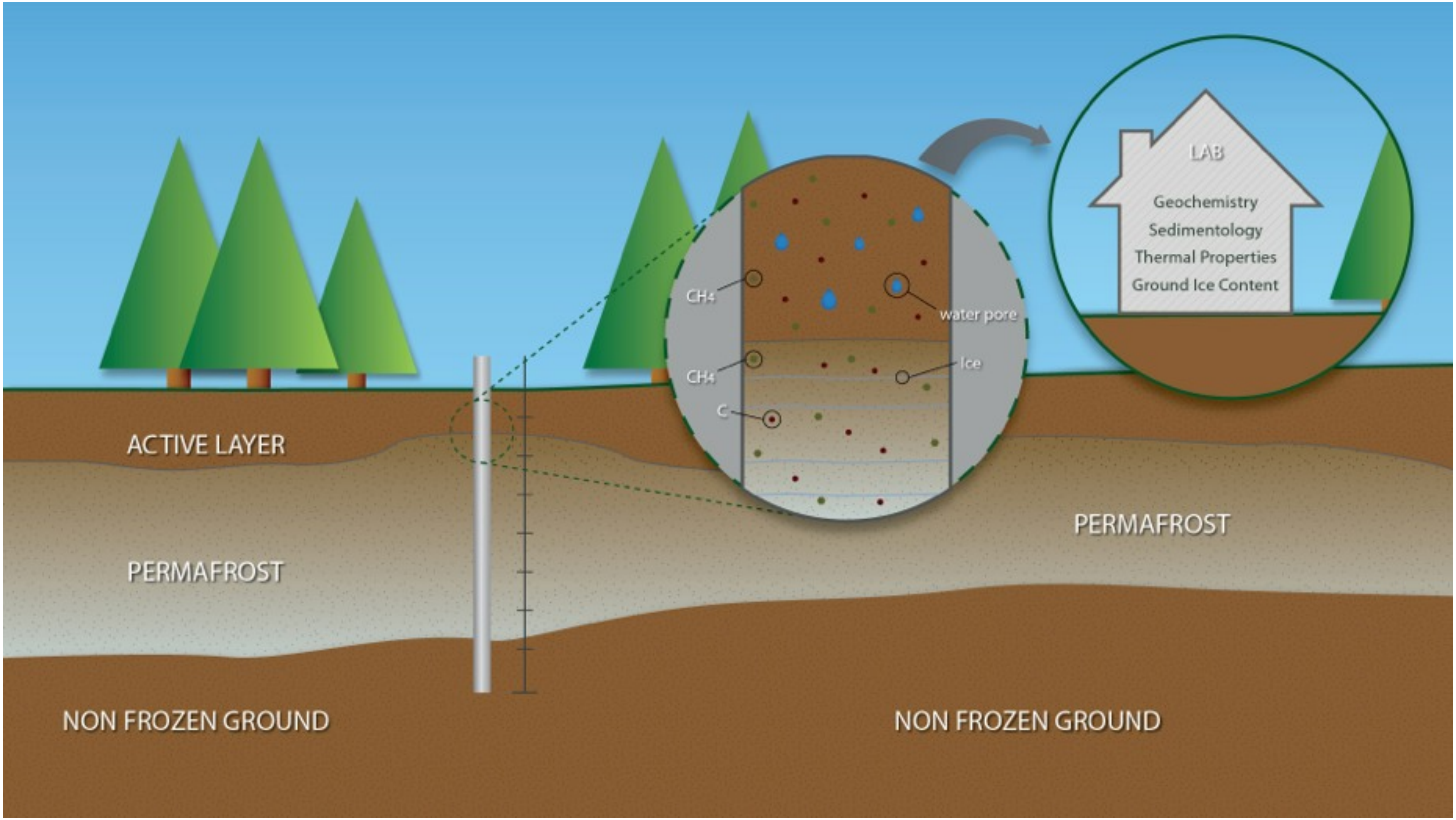
The arctic is a large area and in total it covers almost 25% of the land surface of the Northern Hemisphere. In the field we select our drilling sites on different but typical landforms, such as hill slopes, flat valley bottoms, ice-wedge polygons, etc.

Using a hand-drill we are able to core down to 3m, with a hydraulic drill down to 20m or even deeper.

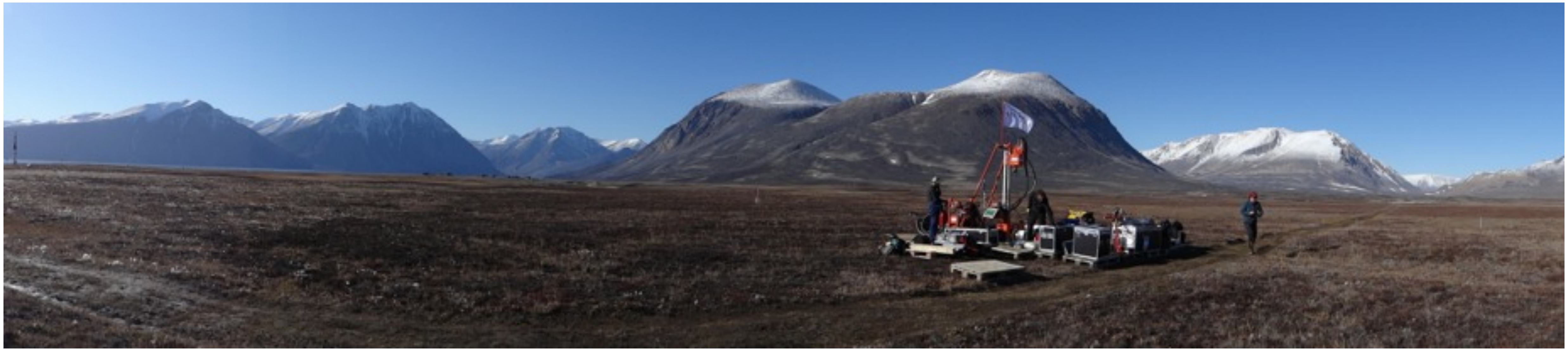
The frozen permafrost cores extracted from the boreholes will be transported frozen to our home institution for analysis.

This is a core taken from a drill in a permafrost area. It shows how ice and soil are frozen together. *Photo: Stefanie Härtel*

Infograph: Permafrost coring *Illustration: Arctic Portal*



Using a hand-drill the researchers are able to core down to 3m, with hydraulic drill down to 20m or even deeper. The frozen permafrost cores extracted from the boreholes are transported frozen to laboratories for analysis.



Immediately after drilling, a chain of thermistors will be installed into the permafrost to monitor ground temperatures at different depths to study its “thermal regime”.

The thermal regime reflects:

1. how low below zero degree the ground temperature differs at depth.
2. how wide the ground temperature ranges from summer to winter.
3. how fast it warms or cools, and
4. if the ground temperature tends to change over a longer period of time. Depending on the type of sediment, snow cover and vegetation the thermal regime can differ a lot at even in the same area.

Typically, permafrost is composed of four elements: sediment or bedrock, organic material and, gas, and importantly, ground ice.

Sometimes, the amount of ice can even exceed the amount of solids. It is very interesting to study the sequence of ice-type and sediment type with depth.

This analysis is referred to as permafrost cryo- and lithostratigraphy. In a freeze lab at temperatures well below zero degree (e.g. -14 °C), we cut the frozen permafrost cores in half and scrape and photograph them to study original structures.

Once we have identified different stratigraphical layers we cut the permafrost core into smaller samples.

In the lab, all the ingredients are elicited from the permafrost samples. The amounts and types of gases stored in permafrost are studied while the samples thaw and after it thawed.

This method is called incubation experiment and can be used to mimic what would happen if parts of the permafrost thaw in the future.

The gases emitted or produced in the sample are extracted and analyzed regarding CO2, CH4 and N2O which are important greenhouse gases. Once the samples are thawed, it is noted how much water and soil the sample contains by volume.

This allows assessing how much the surface would lower, if the permafrost thaws and knowing how much energy is needed to thaw this portion of permafrost and transfer the ice-crystal to a water droplet (so-called latent heat of fusion).

Both the soil water and the sediment are then analyzed regarding very different geochemical and physical characteristics and the material is analyzed to find out how old the soil material is (dating).

The above explained analysis produces a lot of information. In the office at the computer all the data is plotted in many different curves to see how the different parameters change with depth.

A lot of time is spent to think about what the data tells us about the landscape history of the site. A very good understanding of what is happening at the different sites helps us to understand the processes and the history of the entire landscape (up-scaling) and how it may change in the future under climate change.

Permafrost drilling in Samylov. *Photo: Julia Boike*

With the help of the data and aerial images etc, the broader understanding of the landscape is simplified into geomorphological maps showing the different landforms and geocryological maps showing how ground ice content varies in the landscape.

All these outcomes: the stratigraphic data, new knowledge on the landscape history and the maps which show how variable the landscape is, can be used by computer-modelers in many different ways. With the data, they can much better calculate how the landscape would react in the future, if the climate changes.

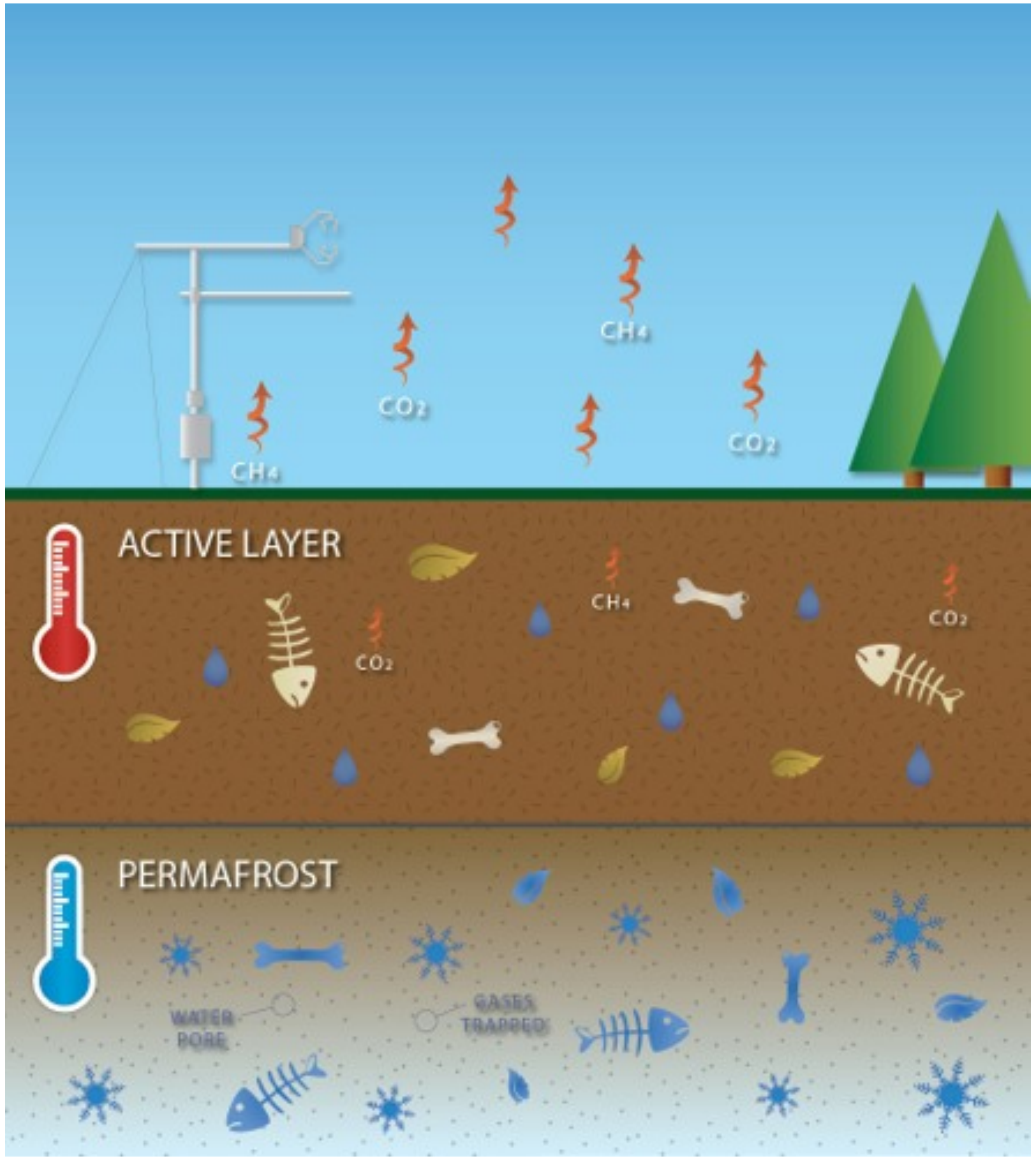
Atmospheric measurements

Arctic soils are an important reservoir of carbon, of which a lot is stored in permafrost. The carbon stored in this reservoir can be exchanged with the atmosphere through the greenhouse gases CO2 and methane, since both of these gases contain carbon.

CO2 is primarily taken up by plants through photosynthesis, and in this way carbon can be added to the soil reservoir. On the other hand, microorganisms in the soil can release carbon from the soil by producing CO2 and methane.

The exchange of these gases is strongly controlled by temperature, sunlight, rain and snowfall. This means that when these factors change, there will be changes in the exchange of CO2 and methane with the atmosphere.

Infograph: Carbon release from permafrost. *Illustration: Arctic Portal*



Since CO_2 and methane are both greenhouse gases, it would mean that climate change in the Arctic could possibly lead to a change of greenhouse gases in the atmosphere.

Whether the release or the uptake of carbon is stimulated most by climate change is still unclear, and that is why it is important to study the exchange of CO_2 and methane in the Arctic.

Eddy covariance is a key atmospheric measurement technique that is used to measure the release and uptake of carbon. It measures and calculates vertical turbulent fluxes and is combined with meteorological measurements, which indicate the conditions in which carbon is exchanged between the atmosphere and permafrost soils.

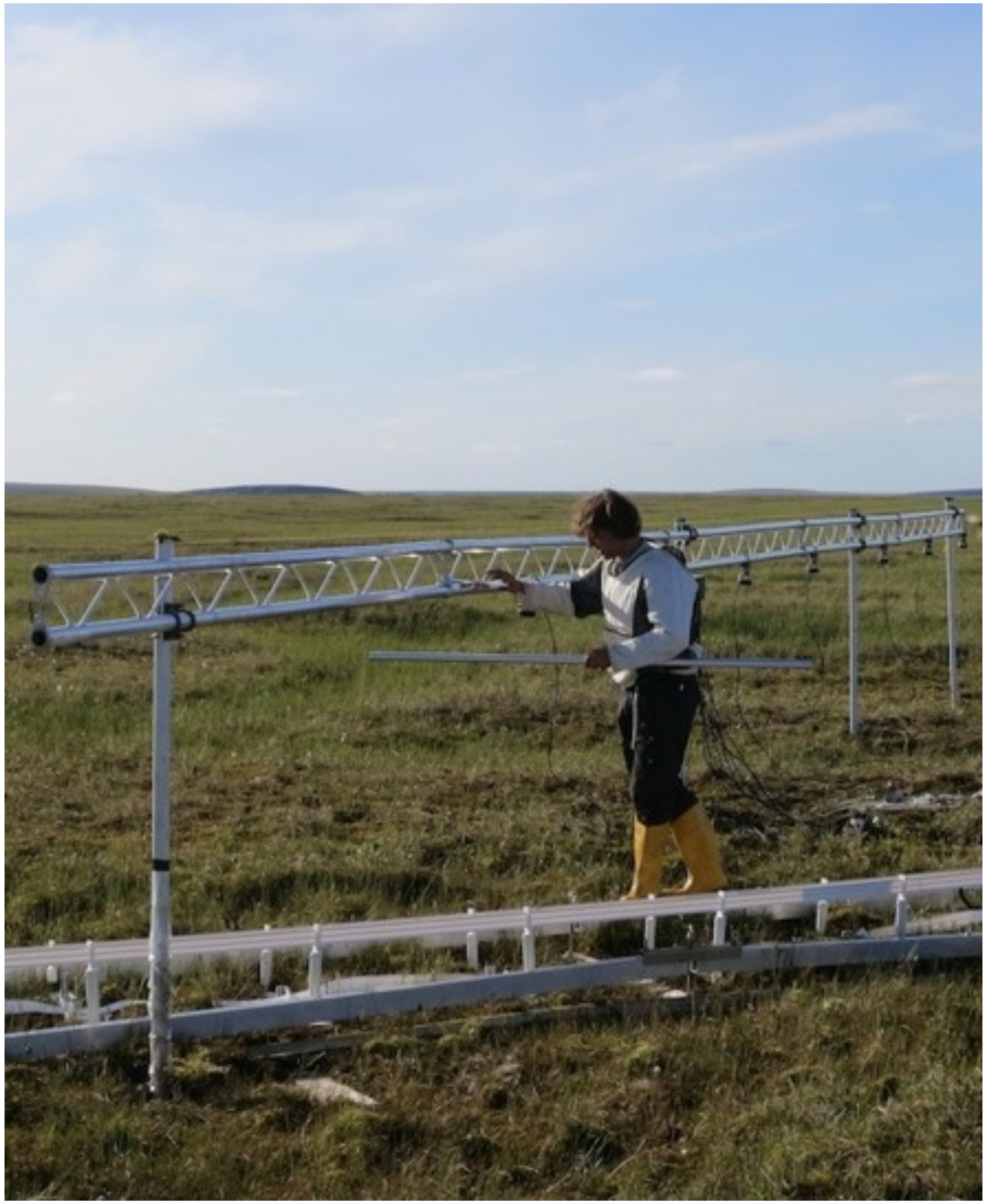
The Eddy covariance tower is key atmospheric measurement technique to measure and calculate vertical turbulent fluxes within atmospheric boundary layers. *Photo: Julia Boike*

Other measurements

Permafrost can be typically found in areas where the mean annual air temperature is less than the freezing point of water, or 0°C. There are, however, exceptions.

These exceptions are most often due to the rich snow cover at least part of the year that acts as an insulating blanket between the permafrost and the atmosphere.

The snow cover and its fluctuation are measured in many permafrost research sites to find out how much impact they have on the permafrost thawing.



Snow consists of a very loose structure of ice crystals and includes a lot of air. Like all porous materials such as foam, snow is a very good thermal insulator and prevents the cooling of the soil in winter. The insulating properties of snow are highly variable, because snow crystals change over time and form distinct layers in the snow. With snow pack analyzer, the differences in snow depth can be measured by using ultrasonic sensors. In addition, using long sensor bands throughout the winter, the changes in snow density can be captured. The snow temperature is measured with thin needles to various depths.

Photo: Max Heikenfeld

Remote Sensing

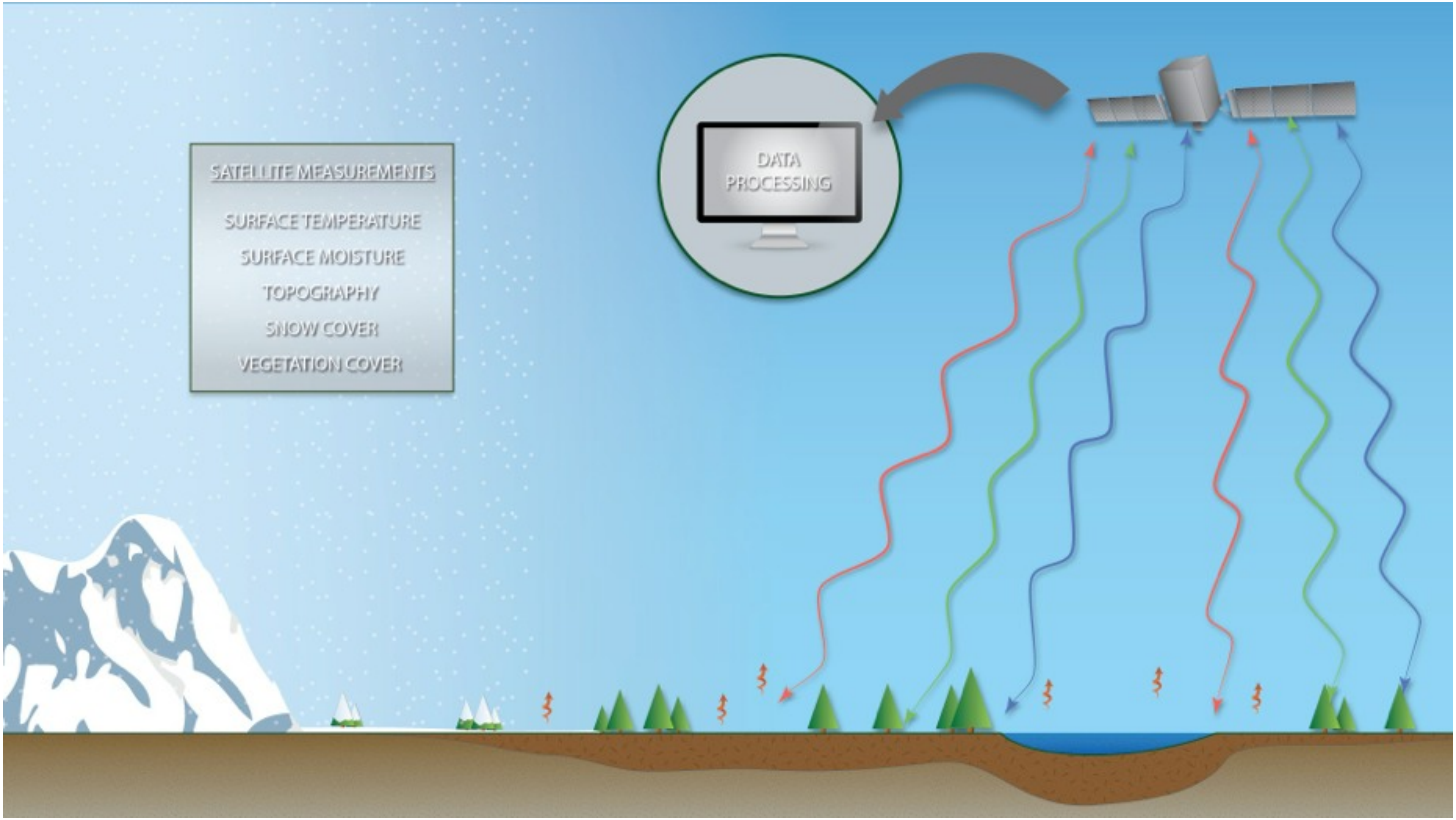
Satellites can also help us understand the earth system in a wider perspective. Remote sensing (satellite observations) offers great potential for detecting changes in permafrost in the context of Arctic warming.

This is especially true for the vast Arctic region where measurements at the ground are rarely available. Satellites carry different sensors which are able to detect different characteristic of the land surface such as vegetation cover, surface temperature, surface moisture, snow cover, and topography.

The satellite measurements give us direct information about the ongoing environmental changes in the Arctic and they are also often required as input for climate models.

Remote sensing is done with satellites. *Photo: GettyImages*

Illustration: Arctic Portal



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