Climate Change and the Arctic
From last week......
Today’s Menu

• What is the Arctic, exactly?
• What are the signs of warming in the Arctic?
• What causes that Warming?
• What are some of the Arctic effects?
What is the Arctic?

The Arctic is at once one of the most beautiful and one of the most forbidding places on Earth and a critical component of the planet's ability to sustain life. In the Arctic, life swings between twenty-four hour days of sunshine in the summer and the long, cold, and dark winter. Despite those harsh conditions, the Arctic is home to vibrant communities and functioning ecosystems. It provides vital habitat for iconic wildlife, including polar bears, whales, walrus, fish, and birds. Arctic peoples have lived a subsistence lifestyle dependent on their environment since time immemorial and continue to do so today. In addition, this region plays a vital role in the planet's climate system.
Polaris....the North Star
Arctic means “Country of the great bear”
The Arctic region is the area around the North Pole, essentially an ocean surrounded by land. In the far north, the Arctic is mostly covered by snow and ice,
whereas the southernmost part is covered by boreal forests. In between, there is a wide expanse of tundra. The Arctic is home to an array of plants, animals, and people that survive in some of the most extreme conditions on the planet and that are uniquely adapted to such conditions…from the algae that live under the sea ice, to the polar bears that live on the ice
Arctic forests
Arctic wildlife
One line used to define the Arctic Circle is the Arctic Circle, which is drawn at the latitude that the sun does not rise above the horizon in the winter and that the sun does not set below the horizon in the summer. The red line indicates the 10°C (50°F) isotherm in July, sometimes used to define the Arctic region border.
The Arctic region is home to almost four million people, including an increasing majority of non-indigenous settlers. The Arctic includes Greenland, Iceland, and the northern parts of Norway, Sweden, Finland, Canada, Russia, and the United States. Economically, the region depends largely on natural resources, ranging from oil, gas, and metal ores to fish, reindeer, and birds. Recently, the tourism sector has also grown in many parts of the Arctic.
Life in the Arctic: Both Vulnerable and Resilient

Life in the Arctic has historically been both vulnerable and resilient. Factors that contribute to the Arctic's vulnerability include its relatively short growing season and smaller variety of living things compared to temperate regions. In addition, arctic climate is highly variable, and a sudden summer storm or freeze can wipe out an entire generation of young birds, thousands of seal pups, or hundreds of caribou calves. Yet some arctic species have also displayed remarkable resilience to historic extremes, as evidenced by the recovery of populations that have occasionally been decimated by climatic variations.
Climate Change as a challenge to resilience...

• The increasingly rapid rate of recent climate change poses new challenges to the resilience of arctic life. In addition to the impacts of climate change, many other stresses brought about by human activities are simultaneously affecting life in the Arctic, including air and water contamination, overfishing, increasing levels of ultraviolet radiation due to ozone depletion, habitat alteration and pollution due to resource extraction, and increasing pressure on land and resources related to the growing human population in the region. The sum of these factors threatens to overwhelm the adaptive capacity of some arctic populations and ecosystems.
Two systems are important in understanding climate change: The carbon cycle and solar radiation.
For understanding climate change we need to understand the role of Carbon dioxide. In the atmosphere, carbon combines with oxygen to produce the gas, CO$_2$. A team of scientists based in Japan and Germany has found an unusual "lake" of liquid carbon dioxide beneath the ocean floor. On Earth's surface carbon dioxide (CO$_2$) is normally a gas, but in the cold, high-pressure ocean depths it cools and becomes a liquid. At less cold temperatures it is solid "dry ice".
The Carbon cycle: The transfer of carbon dioxide from the land to the atmosphere: The Carbon Cycle: long (geological) and short (biological):

- The ocean contains the largest active pool of carbon near the surface of the Earth, but the deep ocean part of this pool does not rapidly exchange with the atmosphere.

- The global carbon cycle can be divided into two categories:
  - the geological cycle, which operates over large time scales (millions of years), and
  - the biological/physical cycle, which operates at shorter time scales (days to thousands of years).

- The global carbon budget is the balance of the exchanges (incomes and losses) of carbon between the carbon reservoirs or between one specific loop (e.g., atmosphere ↔ biosphere) of the carbon cycle.

- Source or Sink
The Geological Carbon cycle: From Carbon to CO$_2$ and back again

In the geological carbon cycle, carbon moves between rocks and minerals, seawater, and the atmosphere. Carbon dioxide in the atmosphere reacts with some minerals to form the mineral calcium carbonate (limestone). This mineral is then dissolved by rainwater and carried to the oceans. Once there, it can precipitate out of the ocean water, forming layers of sediment on the sea floor. As the Earth’s plates move, through the processes of plate tectonics, these sediments are subducted underneath the continents. Under the great heat and pressure far below the Earth’s surface, the limestone melts and reacts with other minerals, releasing carbon dioxide. The carbon dioxide is then re-emitted into the atmosphere through volcanic eruptions.
The biological carbon cycle: From Carbon to CO₂ and back again

- Plants remove CO₂ from the atmosphere through the process of photosynthesis, green plants absorb solar energy and remove carbon dioxide from the atmosphere to produce carbohydrates (sugars).
- Plants and animals effectively “burn” these carbohydrates (and other products derived from them) through the process of respiration, the reverse of photosynthesis.
  - Respiration releases the energy contained in sugars for use in metabolism and renders the carbohydrate “fuel” back to carbon dioxide.
  - Together, respiration and decomposition (respiration that consumes organic matter mostly by bacteria and fungi) return the biologically fixed carbon back to the atmosphere.
  - The amount of carbon taken up by photosynthesis and released back to the atmosphere by respiration each year is 1,000 times greater than the amount of carbon that moves through the geological cycle on an annual basis.

- During times when photosynthesis exceeded respiration, organic matter slowly built up over millions of years to form coal and oil deposits.

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Diagram:
- Carbon dioxide (CO₂) in the atmosphere
- Carbon stored in vegetation
- Carbon in decaying matter and residues
- Carbon stored in soils
- Carbon in fossil fuels released when burned
- Used in photosynthesis to produce carbohydrates
- Plants are eaten by animals
- Carbon stored in fossil fuels
Biological cycle has much more impact on carbon exchange than fossil fuel burning but much of the carbon dioxide released by fossil fuels stays in the atmosphere......
Fire also plays an important role in the transfer of carbon dioxide from the land to the atmosphere. Fires consume biomass and organic matter to produce carbon dioxide (along with methane, carbon monoxide, smoke), and the vegetation that is killed but not consumed by the fire decomposes over time adding further carbon dioxide to the atmosphere.
Warm and cold ocean water

- Carbon dioxide dissolves easily into the ocean and the amount of carbon dioxide that the ocean can hold depends on ocean temperature and the amount of carbon dioxide already present.
- In the oceans, carbon dioxide exchange is largely controlled by sea surface temperatures, circulating currents, and by the biological processes of photosynthesis and respiration.
- Cold ocean temperatures favor the uptake of carbon dioxide from the atmosphere whereas warm temperatures can cause the ocean surface to release carbon dioxide.

Diagram:
- Cold Water absorbs Carbon dioxide
- Warm water releases Carbon dioxide into the atmosphere
- Cold Water absorbs Carbon dioxide
In the atmosphere, some of the CO$_2$ is concentrated and becomes a greenhouse gas.
Now...here comes the sun. Solar radiation powers the climate system.

"SOLAR ENERGY"? - LIKE I DON'T DO ENOUGH FOR THE LITTLE TWERPS ALREADY!
Changes in the sun and changes in the Earth’s orbit: warming and cooling factors

1) Changing the incoming solar radiation (e.g., by changes in Earth’s orbit [Milankovich Cycles] or in the Sun itself)

When the Sun has fewer sunspots, it gives off less energy, less energy makes its way to Earth, and our planet cools down. More than three hundred years ago, when the climate was cooler for a time called the “Little Ice Age”, people noticed there were no sunspots for several decades. Over time, scientists have noticed a pattern in the number of sunspots. About every 11 years the number of sunspots reaches a high and then decreases again.
Once **the Sun's energy** reaches the Earth, **Three things can happen**.

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**Diagram Description**:
- **Energy Received from the Sun**:
  - 342 incoming solar radiation
  - Reflected solar radiation: 107
  - Reflected by clouds, aerosols, and atmosphere: 77
  - Absorbed by the surface: 30
  - Absorbed by the atmosphere: 67
  - Energy flux in Watts per square meter

- **Energy Emitted by the Earth**:
  - Emitted by the surface: 390
  - 235 outgoing longwave radiation
  - Emitted by clouds: 165
  - Transmitted through the atmosphere: 40
  - Absorbed by greenhouse gases: 350
  - Re-emitted radiation: 324

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The diagram illustrates the flow of solar radiation from the Sun to the Earth and the processes by which this energy is distributed and lost back to space.
climate is determined by balance between radiation and absorption

- **Reflected Solar Radiation** — cooling factor
  - About 30% of the sunlight that reaches the top of the atmosphere is reflected back to space. Roughly two-thirds of this reflectivity is due to clouds and small particles in the atmosphere known as 'aerosols'. Light-colored areas of Earth's surface—mainly snow, ice and deserts—reflect the remaining one-third of the sunlight.

- **Absorbed Solar Radiation** — warming factor
  - The energy that is not reflected back to space is absorbed by the Earth's surface and atmosphere. To balance the incoming energy, the Earth itself must radiate, on average, the same amount of energy back to space. The Earth does this by emitting outgoing longwave radiation. Everything on Earth emits longwave radiation continuously. The warmer an object, the more heat energy it radiates.
Global Warming: Balance between warm and cold is disturbed

- According to the IPCC, averaged over all land and ocean surfaces, temperatures have warmed roughly 1.33°F (0.74°C) over the last century, with more than half—about 0.72°F (0.4°C)—having occurred since 1979.
“Forcings”: Volcanos, sunspots, fossil fuel burning

Forcings refer to changes in external factors that affect climate. They are called 'forcings'. External forcings include natural phenomena such as volcanic eruptions and solar variations, as well as human-induced changes in atmospheric composition (anthropogenic forcings).
Cooling factors: albedo....

- Let's take a quick look at a graphic showing how cold air is made.
- Basically, what this graphic is showing us is in the winter when the Arctic is receiving little sunlight, the radiative input is less than the radiative output. In other words, more energy leaves the Earth than is added by the sun and cooling occurs.
Reflecting Solar radiation: cooling factors (forcings)

- **Albedo**: The surface reflectivity of the sun's radiation. Originated from the Latin *albus* meaning "white." It is quantified as the proportion, or percentage of solar radiation of all wavelengths reflected by a body or surface to the amount incident upon it. An ideal white body has an albedo of 100% and an ideal black body, 0%. Albedo values can range between 3% for water at small zenith angles to over 95% for fresh snow. We will revisit this later.

- **Volcanic eruptions**: White upper side of clouds
- **Biomass burning (forest fires)**
- **Burning of coal and oil**
- **Deserts, and dust from sandstorms**
- **Ice and snow**
- **Barren lands**

**Aerosols**: tiny particles of liquid or dust suspended in the atmosphere (most important anthropogenic aerosols is sulphate produced from SO₂)

*Energy reflected*

*Albedo*: ability of a surface to reflect light.

*Sources*: Radiative forcing of climate change, the 1994 report of the scientific assessment working group of IPCC, summary for policymakers, WMO, UNEP; L.D. Danny Harvey, Climate and global environmental change, Prentice Hall, Pearson Education, Harlow, United Kingdom, 2000.
Warming factors: direct absorption and heat trapped by greenhouse gases -- The carbon cycle meets solar radiation

- The main warming factor is the absorption of the sun's heat.
- A second factor is greenhouse gases, which act as a partial blanket for the longwave radiation coming from the surface. This blanketing is known as the natural greenhouse effect. The most important greenhouse gases are water vapor and carbon dioxide.

- Greenhouse Gases:
  - The two most abundant gases in the atmosphere, nitrogen (comprising 78% of the dry atmosphere) and oxygen (comprising 21%) exert almost no greenhouse effect.
  - Instead, the greenhouse effect comes from molecules that are more complex and much less common.
  - Water vapor is the most important greenhouse gas, and carbon dioxide (CO₂) is the second most important one. Methane, nitrous oxide, ozone and several other gases present in the atmosphere in small amounts also contribute to the greenhouse effect.

- Solar radiation combines with the carbon cycle to power the climate system by changing greenhouse gas concentrations, thereby altering the longwave radiation from Earth back towards space.
Feedback

- Feedback mechanisms in the climate system that can either amplify ('positive feedback') or diminish ('negative feedback') the effects of a change in climate forcing.
Feedback Mechanisms

Adding more of a greenhouse gas, such as CO2, to the atmosphere intensifies the greenhouse effect, thus warming Earth’s climate. The amount of warming depends on various feedback mechanisms.

For example, as the atmosphere warms due to rising levels of greenhouse gases, its concentration of water vapor increases, further intensifying the greenhouse effect.

This in turn causes more warming, which causes an additional increase in water vapor, in a self-reinforcing cycle. This water vapor feedback may be strong enough to approximately double the increase in the greenhouse effect due to the added CO2 alone.
One reason the arctic is so important: The Ice-Albedo feedback

1. As snow and ice melt, darker land and ocean surfaces absorb more solar energy.
2. More of the extra trapped energy goes directly into warming rather than into evaporation.
3. The atmospheric layer that has to warm in order to warm the surface is shallower in the Arctic.
4. As sea ice retreats, solar heat absorbed by the oceans is more easily transferred to the atmosphere.
5. Alterations in atmospheric and oceanic circulation can increase warming.
Ice Albedo feedback

Black soot may contribute to melting glaciers and other ice on the planet and eventually a warmer Earth. Traveling potentially thousands of miles from its sources on air currents, this pollution eventually settles out of the air, onto land and into the oceans. On ice and snow, it darkens normally bright surfaces. Just as a white shirt keeps a person cooler in the summer than a black shirt, the vast stretches of polar ice covering much of the planet’s top and bottom reflect large amounts of solar radiation falling on the planet’s surface, helping regulate Earth’s temperature. Soot lowers this albedo, or reflectivity, and the ice retains more heat, leading to increased melting. Soot-darkened ice retains more light, contributing to the process. As light is absorbed, the environment is heated, thus intensifying a feedback loop: a warmer planet yields more ice melting and thus an even warmer planet.
Ice Albedo effect

So what does this have to do with global warming? You have probably heard about concerns over the diminishing ice in Greenland and elsewhere in the Arctic as well as in Antarctica. In areas where the ice melts, revealing land or ocean beneath it, less of the sun's heat is reflected back to space and more is absorbed. Since it is the sun's energy absorbed by the Earth that warms the atmosphere, the melting ice can become a positive feedback and cause the Earth to warm faster.
The Greenhouse Effect

NATURAL GREENHOUSE EFFECT
The greenhouse effect is a natural warming process. Carbon dioxide (CO₂) and certain other gases are always present in the atmosphere. These gases create a warming effect that has some similarity to the warming inside a greenhouse, hence the name “greenhouse effect.”

ENHANCED GREENHOUSE EFFECT
Increasing the amount of greenhouse gases intensifies the greenhouse effect. This side of the globe simulates conditions today, roughly two centuries after the Industrial Revolution began.

Illustration of the greenhouse effect (courtesy of the Marion Koshland Science Museum of the National Academy of Sciences). Visible sunlight passes through the atmosphere without being absorbed. Some of the sunlight striking the earth[1] is absorbed and converted to heat, which warms the surface. The surface[2] emits infrared radiation to the atmosphere, where some of it[3] is absorbed by greenhouse gases and[4] re-emitted toward the surface; some of the heat is not trapped by greenhouse gases and[5] escapes into space. Human activities that emit additional greenhouse gases to the atmosphere[6] increase the amount of infrared radiation that gets absorbed before escaping into space, thus enhancing the greenhouse effect and amplifying the warming of the earth.

Image Source: The National Academy of Sciences
Climate change is not new and it can be abrupt.

An abrupt release of methane, a powerful greenhouse gas, from ice sheets that extended to Earth’s low latitudes some 635 million years ago caused a dramatic shift in climate.

The shift triggered events that resulted in global warming and an ending of the last “snowball” ice age.

The researchers believe that the methane was released gradually at first and then very quickly from clathrates—methane ice that forms and stabilizes beneath ice sheets.

When the ice sheets became unstable, they collapsed, releasing pressure on the clathrates. The clathrates then began to de-gas. Methane clathrate destabilization acted as a runaway feedback to increased global warming, and was the tipping point that ended the last snowball Earth. (The snowball Earth hypothesis posits that the Earth was covered from pole to pole in a thick sheet of ice for millions of years at a time.)

“Our findings document an abrupt and catastrophic global warming that led from a very cold, seemingly stable climate state to a very warm, also stable, climate state—with no pause in between,”

“What we now need to know is the sensitivity of the trigger,” he said. “How much forcing does it take to move from one stable state to the other—and are we approaching something like that today with current carbon dioxide warming?”
The amount of greenhouse gas fluctuates

• The long-term record of atmospheric carbon dioxide obtained from Antarctic ice cores shows huge fluctuations over the past 150,000 years. Periods of low carbon dioxide concentration correspond to ice ages, while higher carbon dioxide concentrations are linked to warmer periods.

• The last ice age ended 10,000 to 20,000 years ago, as carbon dioxide levels rose from below 200 parts per million to about 280 parts per million. Current atmospheric carbon dioxide levels are above 370 parts per million because of the burning of fossil fuels. This has raised concern in the scientific community that average global temperatures may rise as a result.
The last ice age ended 10,000 to 20,000 years ago, as carbon dioxide levels rose from below 200 parts per million to about \textbf{280 parts per million}. Current atmospheric carbon dioxide levels are above \textbf{370 parts per million}. 

![Graph showing carbon dioxide levels over time.](image)
The Human Role

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In addition to the natural fluxes of carbon through the Earth system, anthropogenic (human) activities, particularly fossil fuel burning and deforestation, are also releasing carbon dioxide into the atmosphere.

When we mine coal and extract oil from the Earth's crust, and then burn these fossil fuels for transportation, heating, cooking, electricity, and manufacturing, we are effectively moving carbon more rapidly into the atmosphere than is being removed naturally through the sedimentation of carbon, ultimately causing atmospheric carbon dioxide concentrations to increase.

Also, by clearing forests to support agriculture, we are transferring carbon from living biomass into the atmosphere (dry wood is about 50 percent carbon).

The result is that humans are adding ever-increasing amounts of extra carbon dioxide into the atmosphere. Because of this, atmospheric carbon dioxide concentrations are higher today than they have been over the last half-million years or longer.
Arctic Climate Trends

- Warming
- Melting glaciers and sea ice
- Declining snow cover
- Rising river flows
- Rising temperatures
- Increasing precipitation
- Thawing permafrost
In Alaska and western Canada, average winter temperatures have increased by as much as seven degrees Fahrenheit in the past 600 years.

Changes to the Earth's orbit drove centuries of cooling, but temperatures rose fast in the last 100 years. Scientists took evidence from ice cores, tree rings and lake sediments. The 23 sites sampled were good enough to provide a decade-by-decade picture of temperatures across the region. The result is a "hockey stick"-like curve in which the last decade - 1998-2008 - stands out as the warmest in the entire series.

"The most pervasive signal in the reconstruction, the most prominent trend, is the overall cooling that took place for the first 1,900 years," said study leader Darrell Kaufman from Northern Arizona University in Flagstaff, US. "The 20th Century stands out in strong contrast to the cooling that should have continued. The last half-century was the warmest of the 2,000-year temperature record, and the last 10 years have been especially dramatic," he told BBC News.

The research shows a long, slow cooling followed by an abrupt warming. Much debate on climate change has centred on the Mediaeval Warm Period, or Mediaeval Climate Anomaly - a period about 1,000 years ago when, historical records suggest, Vikings colonised Greenland and may have grown grapes in Newfoundland.

The new analysis shows that temperatures were indeed warmer in this region 1,000 years ago than they were 100 years ago - but not as warm as they are now, or 1,000 years previously. "It shows that the Mediaeval Warm Period is real, and is... an exception from the general trend of cooling," "It also shows there's lots of variability on the 100-year timescale, and that's probably more so in the Arctic than elsewhere."
The last half-century is the warmest of the 2,000-year temperature record, and the last 10 years have been especially dramatic.
Melting glaciers

Muir and Riggs Glaciers

2004

1941
Decline of the snow cover

Snow cover extent has declined by 10 per cent over the last 30 years.

Mean snow cover extent (grey), 1966-2006, for February (left) and August (right) from the Northern Hemisphere Equal Area Scalable Earth (EASE)-Grid Weekly Snow Cover and Sea Ice Extent data set (Armstrong and Brodzik, 2005). The product includes climatologies of snow average conditions, probability of occurrence, and variance based on NOAA charts as revised by Robinson et al. (1993).
Melting snow.......
Increasing precipitation

On a warmer Earth, there has to be more rain. But drought is clobbering the American Southwest; Australia's rice regions are dust; where's it coming down?

Rain has increased by 8 per cent over the last century. In addition to the overall increase, changes in the characteristics of precipitation have also been observed. Much of the precipitation increase appears to be coming as rain, mostly in winter, and to a lesser extent in autumn and spring. The increasing winter rains, which fall on top of existing snow, cause faster snowmelt and, when the rainfall is intense, can result in flash flooding in some areas. Rain-on-snow events have increased significantly across much of the Arctic, for example, by 50% over the past 50 years in western Russia.
Projected precipitation

- Global warming will lead to increased evaporation and in turn to increased precipitation (this is already occurring). Over the Arctic as a whole, annual total precipitation is projected to increase by roughly 20% by the end of this century, with most of the increase coming as rain.
- During the summer, precipitation over northern North America and Chukotka, Russia is projected to increase, while summer rainfall in Scandinavia is projected to decrease.
- During winter, precipitation for virtually all land areas (except southern Greenland) is projected to increase. The increase in arctic precipitation is projected to be most concentrated over coastal regions and in the winter and autumn; increases during these seasons are projected to exceed 30%.
The sea ice presently covering the Arctic Ocean and neighboring seas is highly sensitive to temperature changes of the air and of the ocean. Over the past 30 years, the average area covered by sea ice has decreased by about 8%, an area larger than Norway, Sweden and Denmark combined. The average thickness of Arctic sea ice has also decreased by about 10 to 15% over this time period. A reduction of sea ice as a result of the warming climate can in turn affect the climate through changes in water temperatures, ocean currents, and ocean evaporation rates.
Projected sea ice decline

- Additional declines of roughly 10-50% in annual average sea ice extent are projected by 2100.
- Loss of sea ice during summer is projected to be considerably greater than the annual average decrease, with a 5-model average projecting more than a 50% decline by the end of this century, and some models showing near-complete disappearance of summer sea ice.
- The projected reductions in sea ice will increase regional and global warming by reducing the reflectivity of the ocean surface.
Rising sea level...
Expansion of forests

• With Arctic warming, forests are projected to expand northward into areas that are currently tundra. Forests are darker than tundra and mask snow cover on the ground, reducing the reflection of sunlight and further increasing warming. However, the resulting warming could be partly offset by larger expanses of forests absorbing more CO$_2$. 
Thawing permafrost

Permafrost has warmed up by 2 degrees centegrade in recent decades and the depth of the layer that thaws each year is increasing. The southern limit will shift northward by several km in the coming year.

The thawing of permafrost in northern latitudes, which greatly increases microbial decomposition of carbon compounds in soil, will dominate other effects of warming in the region and could become a major force promoting the release of carbon dioxide and thus further warming.
Increase in Methane
An acclaimed photographer teams up with scientists to document the runaway melting of arctic glaciers.