

# Trace gas fluxes in Permafrost

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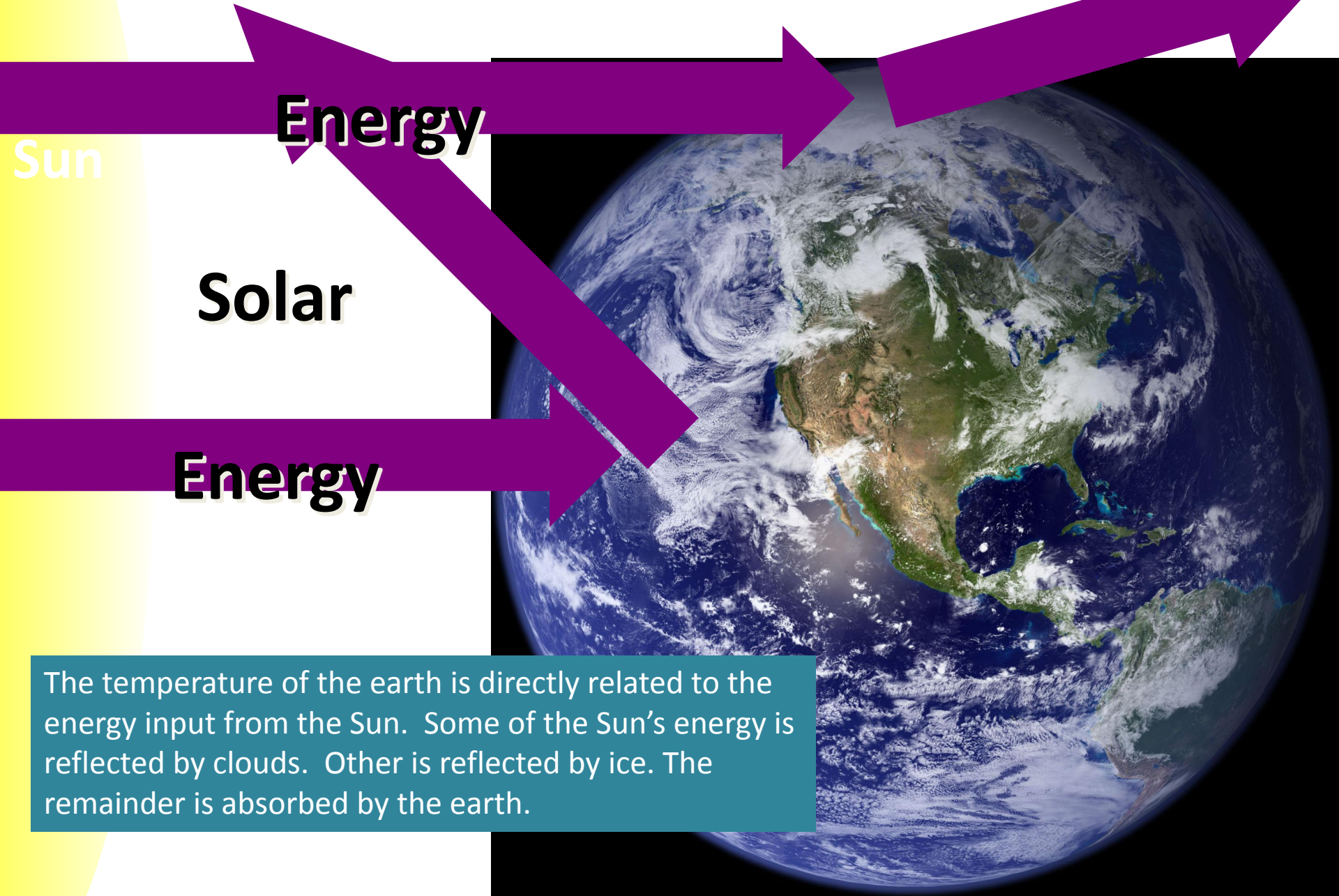
# History of Earth's Climate

- Earth formed ~4.6 billion years ago
- Originally very hot
- Sun's energy output only 70% of present
- Liquid water present ~4.3 billion years

# History of Earth's Climate

- Life appeared ~3.8 billion years ago
- Photosynthesis began 3.5-2.5 billion years ago
  - Produced oxygen and removed carbon dioxide and methane (greenhouse gases)
  - Earth went through periods of cooling (“Snowball Earth”) and warming
- Earth began cycles of glacial and interglacial periods ~3 million years ago

# Solar Earth's Temperature



Sun

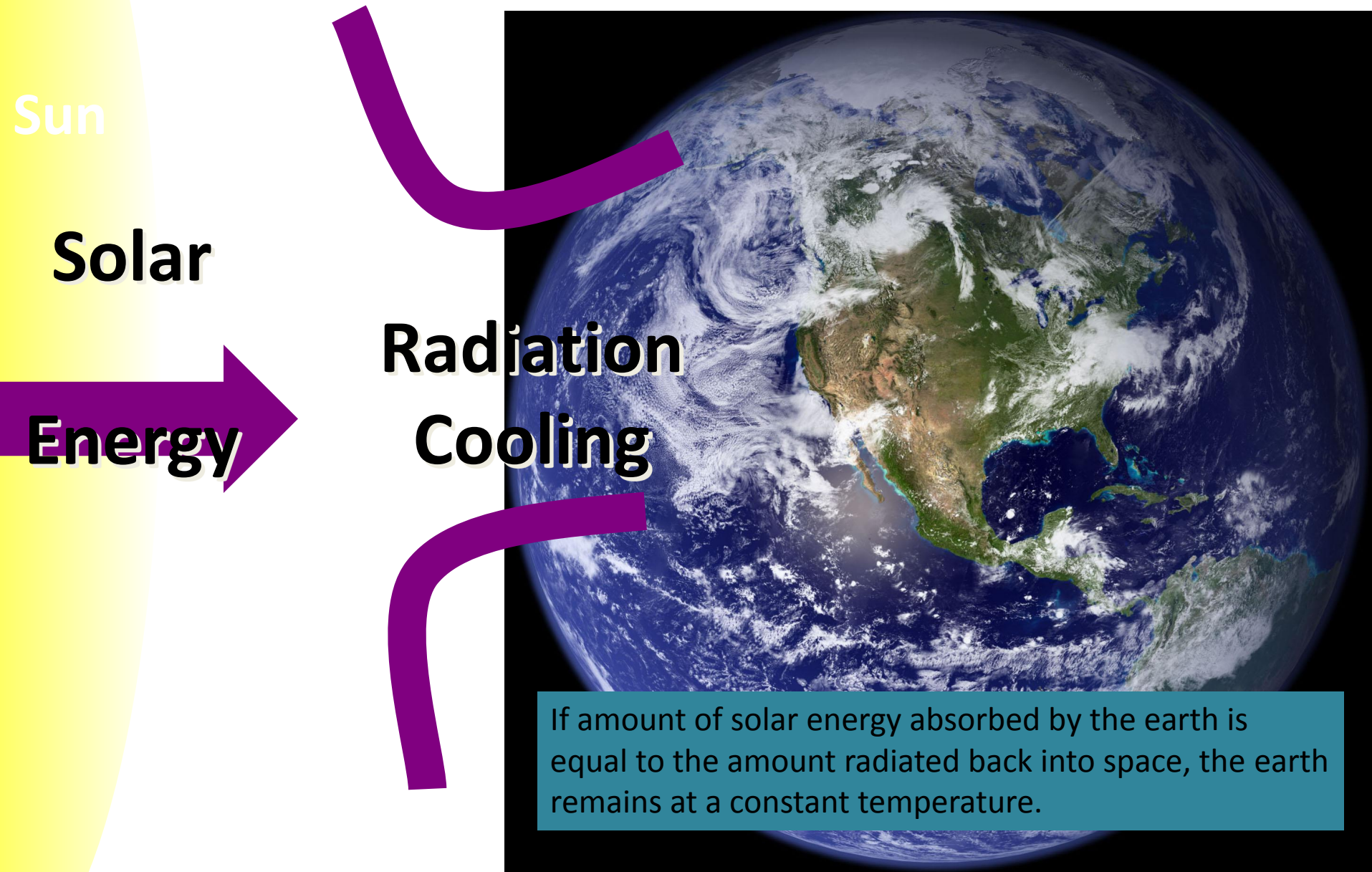
Energy

Solar

Energy

The temperature of the earth is directly related to the energy input from the Sun. Some of the Sun's energy is reflected by clouds. Other is reflected by ice. The remainder is absorbed by the earth.

# Earth's Temperature



Sun

Solar

Energy

Radiation  
Cooling

If amount of solar energy absorbed by the earth is equal to the amount radiated back into space, the earth remains at a constant temperature.



# Earth's Temperature

**Solar**

Sun

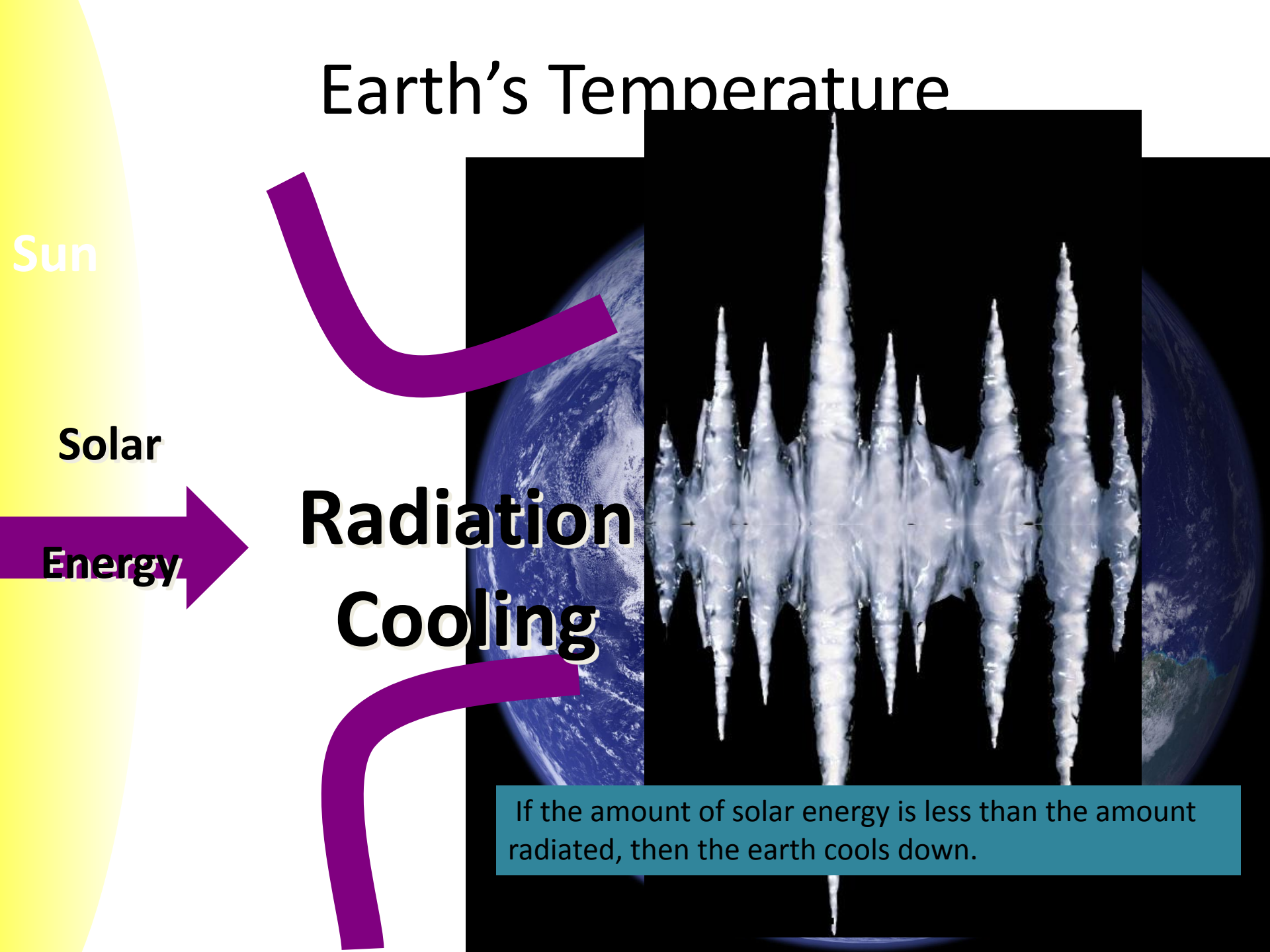
**Energy**

**Radiation  
Cooling**

if the amount of solar energy is greater than the amount radiated, then the earth heats up.



# Earth's Temperature



Sun

Solar

Energy

**Radiation  
Cooling**

If the amount of solar energy is less than the amount radiated, then the earth cools down.

Sun

# Greenhouse Effect



To a certain degree, the earth acts like a greenhouse. Energy from the Sun penetrates the glass of a greenhouse and warms the air and objects within the greenhouse. The same glass slows the heat from escaping, resulting in much higher temperatures within the greenhouse than outside it.



# Earth's Atmospheric Gases

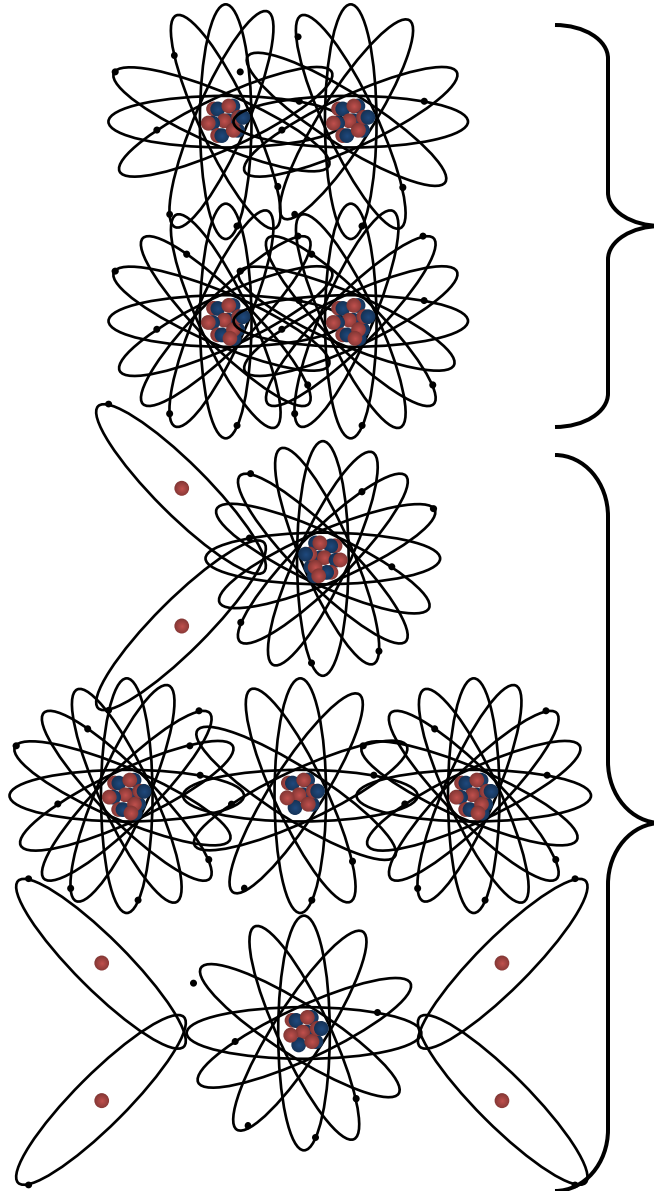
Nitrogen ( $N_2$ )

Oxygen ( $O_2$ )

Water ( $H_2O$ )

Carbon Dioxide ( $CO_2$ )

Methane ( $CH_4$ )



**Non-  
Greenhouse  
Gases  
99%**

**Greenhouse  
Gases  
1%**

by Laurent Cousineau (Montreal)

<http://www.climate-change-guide.com/global-warming-potential-definition.html>

- A *trace gas* is a gas that makes up an extremely small portion of a mixture of gases.
- When discussing [climate change](#), *trace gas* refers to any of the less common gases found in the Earth's [atmosphere](#).

Essentially, nitrogen and oxygen are the most common gases representing about 78.1% and 20.9% of the Earth's atmosphere respectively.

Hence, every other gas is considered a trace gas.

These include:

[carbon dioxide](#)

- [methane](#)
- [oxides of nitrogen](#)
- [ozone](#)
- [water vapor](#)
- ammonia
- argon (the most abundant trace gas representing about 0.934% of the Earth's atmosphere)
- Despite their very small concentrations, trace gases have several important effects on both the Earth's [weather](#) and [climate](#).

More importantly, many of the gases mentioned above are [greenhouse gases](#) responsible for the [greenhouse effect](#).

by Laurent Cousineau (Montreal)

<http://www.climate-change-guide.com/global-warming-potential-definition.html>

- Global Warming Potential Definition
- The global warming potential (GWP) of a gas is measure of its total contribution to [global warming](#).

More specifically, it measures the warming impact from the emission of one unit of a certain gas when compared to one unit of carbon dioxide.

Carbon dioxide is the reference gas and is thus assigned a value of 1.

The values found below originate from the [IPCC](#)'s Fourth Assessment Report in 2007:

- GasGWP
- [Carbon Dioxide](#) 1
- [Methane](#) 25
- [Nitrous Oxide](#) 298
- [Hydrofluorocarbons](#) 140 to 11,700
- [Erfuorocarbons](#) 7,390 to 12,200
- [Sulfur Hexafluoride](#) 22 800

- Climate Feedback Definition
- A *climate feedback* is a process that will either amplify or reduce *climate forcing*.

Climate forcing, also known as radiative forcing, refers to changes in net irradiance between the different layers of the [atmosphere](#).

These changes in irradiance (the power of electromagnetic radiation per unit area) will either cause a cooling or warming effect.

- Positive Feedback Loops
- There are many positive feedback loops that will accelerate [global warming](#).

For example, as more ice melts due to global warming, there will be less sunlight reflected away ([albedo](#)) and consequently, surface temperatures will increase.

Also, global warming will cause more wild fires which will release large amounts of carbon dioxide into the atmosphere which will in turn cause even more warming via the [greenhouse effect](#).

Yet another example, as global warming melts permafrost in both Northern Canada and Siberia, huge amounts of methane, a powerful [greenhouse gas](#), will be released into the atmosphere.

- In addition, mankind is currently increasing its annual carbon dioxide emissions which will even further accelerate global warming.

Truly, we need to unite and [stop climate change](#) before we hit a point of no return.



- Carbon Dioxide Definition
- Carbon dioxide (CO<sub>2</sub>) is the primary [anthropogenic greenhouse gas](#) responsible for [global warming](#).

Although carbon dioxide is a naturally occurring gas, it is also released into the [atmosphere](#) as a result of:

- [biomass](#)
  - [fossil fuel](#) combustion (as a by-product)
  - land-use changes
  - various industrial processes
  - Moreover, carbon dioxide is given a [global warming potential](#) of 1 and all other greenhouse gases are measured against it.
- Greenhouse Gases
- [Carbon Dioxide](#)
  - [Chlorofluorocarbons](#)
  - [Hydrochlorofluorocarbons](#)
  - [Hydrofluorocarbons](#)
  - [Methane](#)
  - [Nitrous Oxide](#)
  - [Ozone](#)
  - [Perfluorocarbons](#)
  - [Sulfur Hexafluoride](#)
  - [Water Vapour](#)

- Methane Definition
- Methane (CH<sub>4</sub>) is a hydrocarbon and an important [greenhouse gas](#).

According to the [IPCC's](#) Fourth Assessment Report in 2007, methane has a [global warming potential](#) 25 times stronger than [carbon dioxide](#).

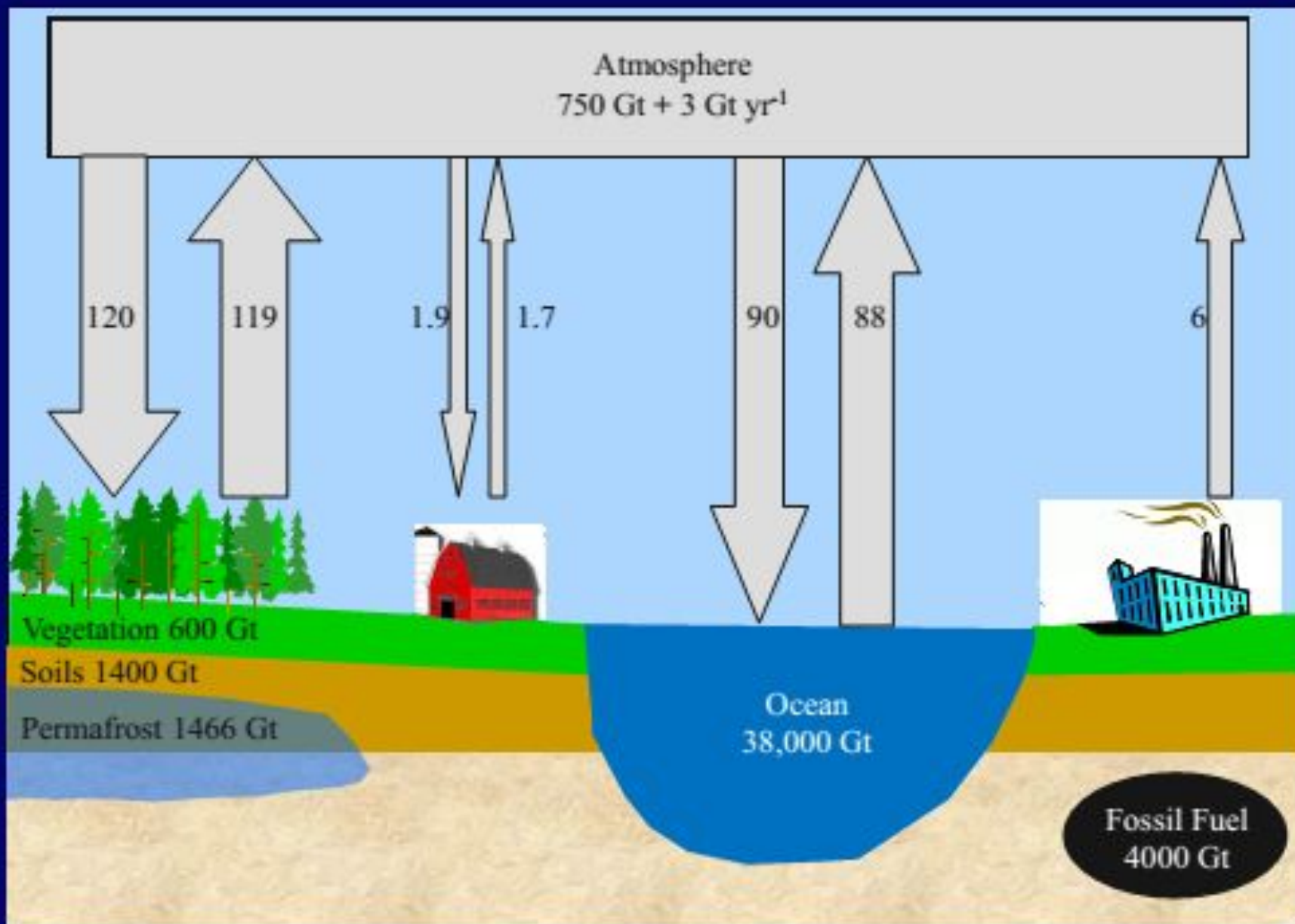
In general, methane is produced from:

- anaerobic (without oxygen) decomposition of waste in landfills
- animal digestion
- coal production
- decomposition of animal wastes
- incomplete fossil fuel combustion
- production and distribution of natural gas and petroleum
- Positive Feedback Loop
- There is an important [climate feedback](#) regarding methane gas.

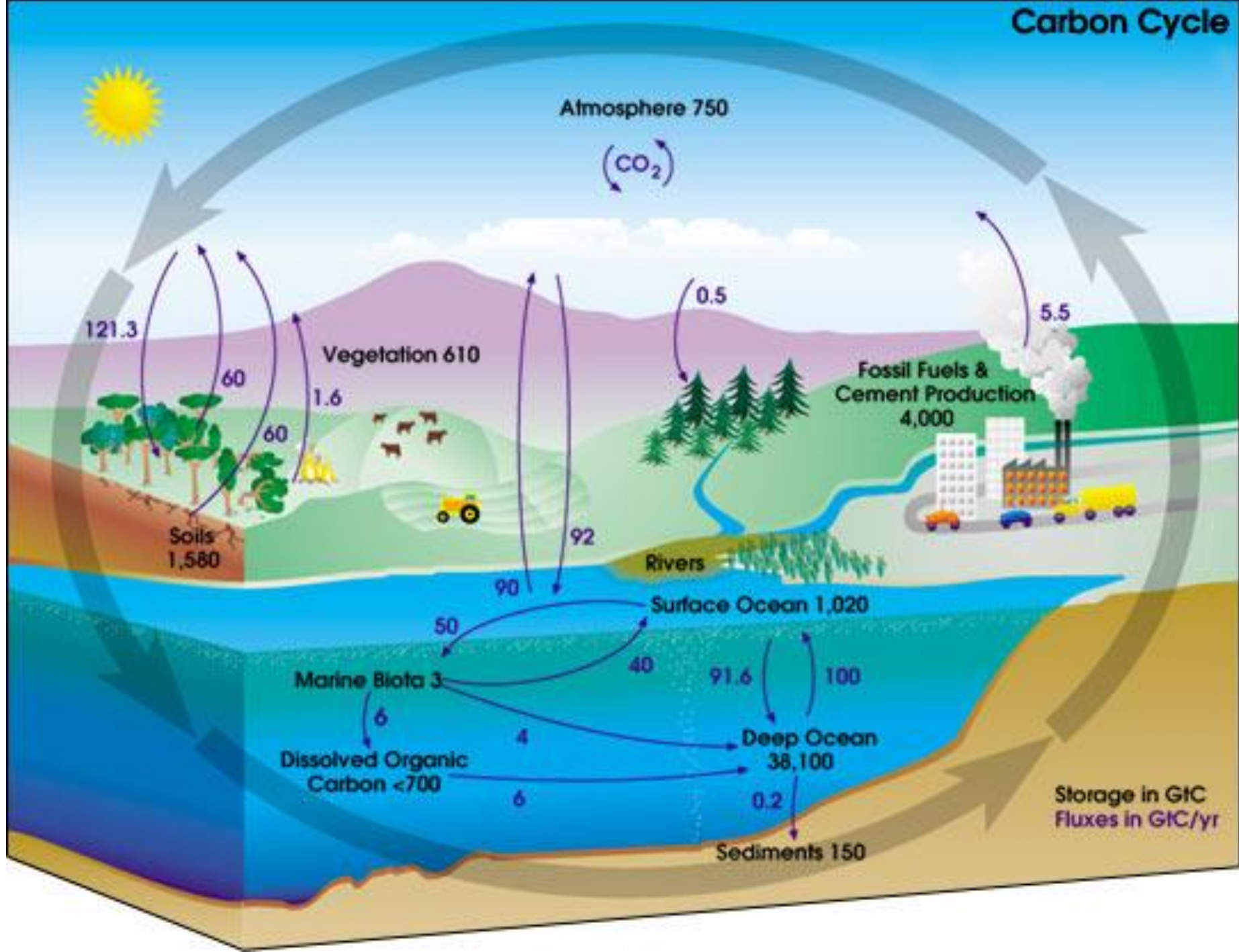
Notably, as temperatures rise worldwide, permafrost in both Northern Canada and Siberia will melt which will cause huge amounts of methane to be released into the [atmosphere](#).

Since methane is a greenhouse gas, this will cause even more [global warming](#) which will further enhance the melting of permafrost. Greenhouse Gases

# Global Carbon Cycle



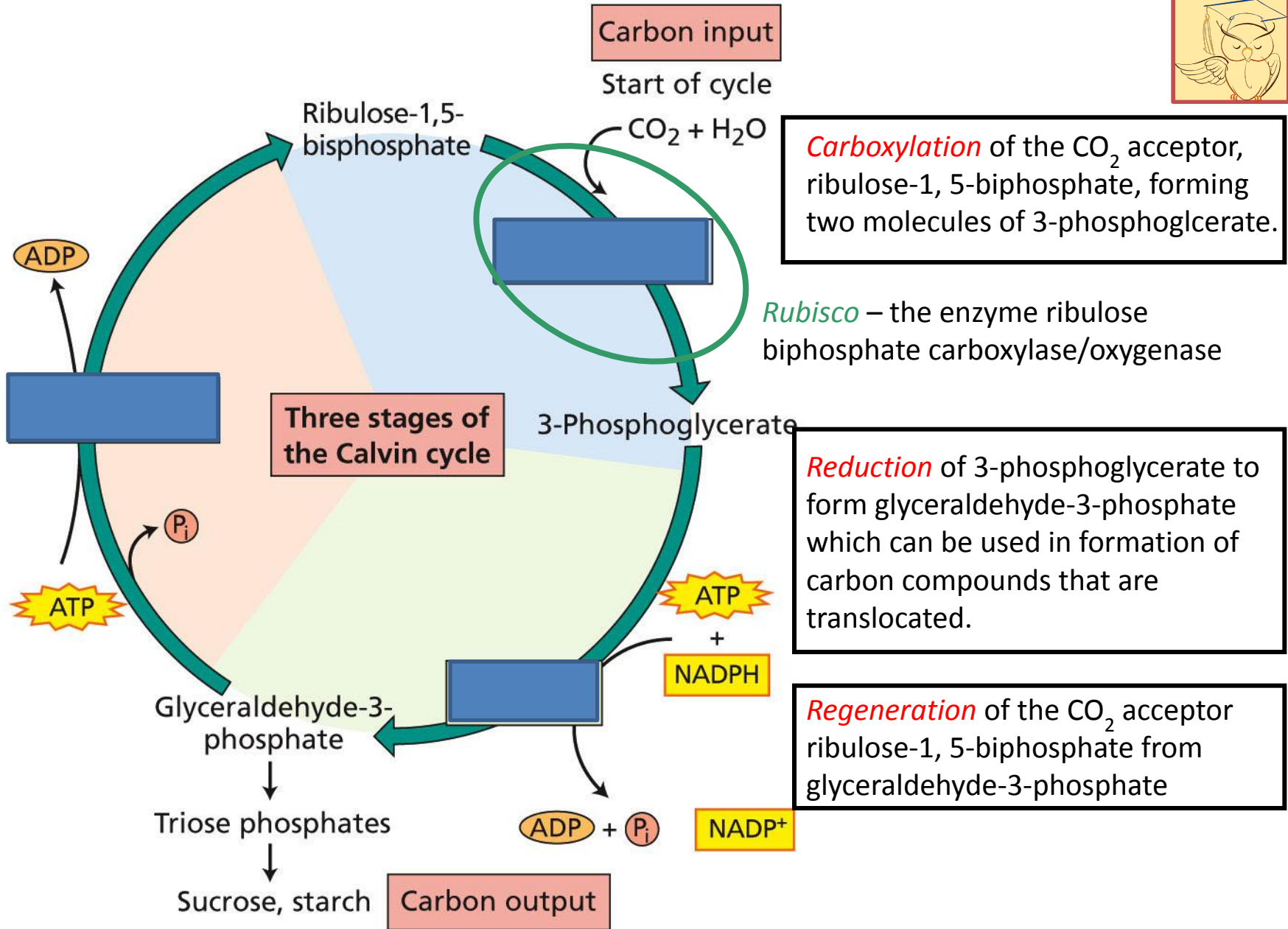
# Carbon Cycle





- Natural sources of atmospheric carbon dioxide include [volcanic outgassing](#), the [combustion](#) of [organic matter](#), [wildfires](#) and the [respiration](#) processes of living [aerobic organisms](#). Man-made sources of carbon dioxide include the burning of [fossil fuels](#) for heating, [power generation](#) and [transport](#), as well as some industrial processes such as cement making. It is also produced by various [microorganisms](#) from [fermentation](#) and [cellular respiration](#). [Plants](#), [algae](#) and [cyanobacteria](#) convert carbon dioxide to [carbohydrates](#) by a process called [photosynthesis](#).
- Atmospheric carbon dioxide plays an integral role in the Earth's carbon cycle whereby carbon dioxide is removed from the atmosphere by some natural processes such as [photosynthesis](#) and deposition of carbonates, to form limestones for example, and added back to the atmosphere by other natural processes such as [respiration](#) and the acid dissolution of carbonate deposits.
- Photosynthetic organisms are [photoautotrophs](#), which means that they are able to [synthesize](#) food directly from CO<sub>2</sub> and water using energy from light.
- In plants, algae and cyanobacteria, photosynthesis releases oxygen.
- Carbon dioxide is converted into sugars in a process called [carbon fixation](#).
- Carbon fixation is an [endothermic redox](#) reaction, so photosynthesis needs to supply both a source of energy to drive this process, and the electrons needed to convert CO<sub>2</sub> into a [carbohydrate](#). This addition of the electrons is a [reduction reaction](#). In general outline and in effect, photosynthesis is the opposite of [cellular respiration](#), in which glucose and other compounds are oxidized to produce CO<sub>2</sub> and water, and to release [exothermic](#) chemical energy to drive the organism's [metabolism](#). However, the two processes take place through a different sequence of chemical reactions and in different cellular compartments.

# The Calvin cycle proceeds in three stages: carboxylation, reduction, and regeneration



# K-STATE

## Research and Extension

### “What is the difference between C3 plants and C4 plants?”

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Animals need to eat all year round, however there is no “all season” plant to use for forage. Knowing this allows us to view the plants in their seasonal and photosynthetic. These patterns can be characterized by C3 plants (cool-season, temperate) and C4 plants (warm-season, tropical). It is these growth patterns that are the basic key to having quality forage all year long.

C3 and C4 plants both use the process of photosynthesis to convert light to energy and atmospheric CO<sub>2</sub> into plant food energy (carbohydrates). The plants differ in the leaf anatomy and enzymes used to carry out photosynthesis. These differences are important with respect to their optimal growing conditions, nitrogen and water-use efficiency, forage quality, and seasonal production profile.

#### Sunlight

Carbon dioxide (CO<sub>2</sub>) + water (H<sub>2</sub>O) -> carbohydrate (food) + oxygen (O<sub>2</sub>)  
Green plant material

### **C3 Plants- Cool Season Plants**

C3 plants are called temperate or cool-season plants. They reduce (fix) CO<sub>2</sub> directly by the enzyme ribulose biphosphate carboxylase (RUBPcase) in the chloroplast. The reaction between CO<sub>2</sub> and ribulose biphosphate, a phosphorylated 5-carbon sugar, forms two molecules of a 3-carbon acid. This 3-carbon acid is called 3-phosphoglyceric acid and explains why the plants using this reaction are called C3 plants.

C3 plants have an optimum temperate range of 65-75°F. Growth begins when the soil temperature reaches 40-45°F. C3 plants become less efficient as the temperature increases. However, they provide a higher percentage of crude protein than C4 plants. Cool-season grasses are productive in the spring and fall because of the cooler temperatures during the day and night, shorter photoperiods, and higher soil moisture. During the summer, growth is reduced and dormancy is induced by high temperatures and low precipitation.

C3 plants can be annual or perennial. Annual C3 plants include wheat, rye, and oats. Perennial C3 plants include orchardgrass, fescues, and perennial ryegrass. The breakdown of C3 plants in the rumen of the Bovine is often faster than C4 grasses because of the thin cell walls and leaf tissues and are therefore often higher in forage quality.

### **C4 Plants- Warm-Season Plants**

C4 plants are often called tropical or warm season plants. They reduce carbon dioxide captured during photosynthesis to useable components by first converting carbon dioxide to oxaloacetate, a 4-carbon acid. This is the reason these plants are referred to as C4 plants. Photosynthesis then continues in much the same way as C3 plants. This type of photosynthesis is highly efficient and little fixed CO<sub>2</sub> is lost through photorespiration.

C4 plants are more efficient at gathering carbon dioxide and utilizing nitrogen from the atmosphere and in the soil. They also use less water to make dry matter. C4 plants grow best at 90-95°F. They begin to grow when the soil temperature is 60-65°F. Forage of C4 species is generally lower in protein than C3 plants but the protein is more efficiently used by animals.

C4 plants can be annual or perennial. Annual C4 plants include corn, sudangrass, and pearl millet. Perennial C4 plants include big bluestem, indiangrass, bermudagrass, switchgrass, and old world bluestem.



# Net Ecosystem Exchange (NEE)

$$\text{NEE} = \text{Respiration} - \text{Photosynthesis}$$



Enhanced by  
Permafrost  
Carbon  
Feedback



Enhanced  
by CO<sub>2</sub>  
Fertilization

- $\text{NEE} < 0$  means net carbon uptake

- • There is a clear correlation between the amount of anthropogenic CO<sub>2</sub> released to the atmosphere and the increase in atmospheric CO<sub>2</sub> concentration during last decades.
- • Atmospheric oxygen is declining proportionately to CO<sub>2</sub> increase and fossil fuel combustion. • For the last half century, the CO<sub>2</sub> airborne fraction (AF) parameter remained consistent and averaged at 0.55 (the AF parameter is the ratio of the increase in atmospheric CO<sub>2</sub> concentration to fossil fuel-derived CO<sub>2</sub> emissions). AF has been introduced to assess short- and long-term changes in the atmospheric carbon content; in particular, AF of 0.55 indicates that the oceans and terrestrial ecosystems have cumulatively removed about 45 % of anthropogenic CO<sub>2</sub> from the atmosphere over the last half century [6].
- • The isotopic signature of fossil fuels (e.g., the lack of <sup>14</sup>C and the depleted level of <sup>13</sup>C carbon isotopes) is detected in atmospheric CO<sub>2</sub>. • There exists an interhemispheric gradient in the atmospheric CO<sub>2</sub> concentrations in the Northern and Southern Hemispheres. In particular, the predominance of fossil-derived CO<sub>2</sub> emissions in more industrially developed Northern Hemisphere (compared to the Southern Hemisphere) causes the occurrence of the atmospheric CO<sub>2</sub> gradient in the amount of about 0.5 ppm per GtC per year [6].
- • There have been dramatic changes in R<sub>FCO<sub>2</sub></sub> values over the last decades. For example, during 1995–2005, the R<sub>FCO<sub>2</sub></sub> increased by about 0.28 W/m<sup>2</sup> (or about 20 % increase), which represents the largest increase in R<sub>FCO<sub>2</sub></sub> for any decade since the beginning of the industrial era. R<sub>FCO<sub>2</sub></sub> in 2005 was estimated at R<sub>FCO<sub>2</sub></sub>=1.66±0.17 W/m<sup>2</sup> (corresponding to the atmospheric CO<sub>2</sub> concentration of 379±0.65 ppm), which is the largest RF among all major forcing factors (The concept of radiative forcing (RF))
- • The data show that the changes in the land use greatly contributed to the R<sub>FCO<sub>2</sub></sub> value in the amount of about 0.4 W/m<sup>2</sup> (since the beginning of the industrial era). This implies that the remaining three quarters of R<sub>FCO<sub>2</sub></sub> can be attributed to burning fossil fuels, cement manufacturing, and other industrial CO<sub>2</sub> emitters [6].

Methane in the Earth's atmosphere is a strong [greenhouse gas](#) with a [global warming potential](#) of 29 over a 100-year period. This means that a methane emission will have 29 times the impact on temperature of a carbon dioxide emission of the same mass over the following 100 years. Methane has a large effect (24 times as strong as carbon dioxide per unit [mole](#)) for a brief period (having an estimated lifetime of  $8.9 \pm 0.6$  years in the atmosphere),<sup>[8]</sup> whereas carbon dioxide has a small effect for a long period (over 100 years). Because of this difference in effect and time period, the global warming potential of methane over a 20-year time period is 86.

- A. [Permafrost](#), [glaciers](#), and [ice cores](#) – A source that slowly releases methane trapped in frozen environments as global temperatures rise.
- B. [Wetlands](#) – Warm temperatures and moist environments are ideal for methane production.<sup>[10]</sup> Most of the methane makes it past methane-consuming microorganisms.<sup>[citation needed]</sup>
- C. [Forest fire](#) – Mass burning of organic matter releases methane into the atmosphere.<sup>[11]</sup>
- D. [Rice paddies](#) – The warmer and moister the rice field, the more methane is produced.
- E. [Animals](#) – Microorganisms breaking down difficult to digest material in the guts of ruminant livestock and termites produce methane that is then released during defecation.
- F. [Plants](#) – While methane can be consumed in soil before being released into the atmosphere, plants allow for direct travel of methane up through the roots and leaves and into the atmosphere.<sup>[12]</sup> Plants may also be direct producers of methane.<sup>[13]</sup>
- G. [Landfills](#) – Decaying organic matter and anaerobic conditions cause landfills to be a significant source of methane.
- H. [Waste water treatment facilities](#) – Anaerobic treatment of organic compounds in the water results in the production of methane.

The balance between sources and sinks of methane is not yet fully understood. The [IPCC Working Group I](#) stated in chapter 2 of the Fourth Assessment Report that there are "large uncertainties in the current bottom-up estimates of components of the global source", and the balance between sources and sinks is not yet well known. The most important sink in the methane cycle is reaction with the hydroxyl radical, which is produced photochemically in the atmosphere. Production of this radical is not fully understood and has a large effect on atmospheric concentrations.

- I. [Hydroxyl radical](#) – OH in the atmosphere is the largest sink for atmospheric methane as well as one of the most significant sources of water vapor in the upper atmosphere
- J. [Chlorine radical](#) – Free chlorine in the atmosphere also reacts with methane.

- На эти две реакции с OH приходится около 90% удаления метана из атмосферы. Кроме реакции с OH известно еще два процесса: микробиологическое поглощение метана в почвах и реакция метана с атомами хлора (Cl) на поверхности моря. Вклад этих процессов 7% и менее 2% соответственно.<sup>[5]</sup>



# Pervasiveness of Life

Earth life extraordinarily successful

Natural selection & evolution

--> adaptability

Organisms found EVERYWHERE

glaciers & permafrost

hot springs

hydrothermal vents

desert rocks

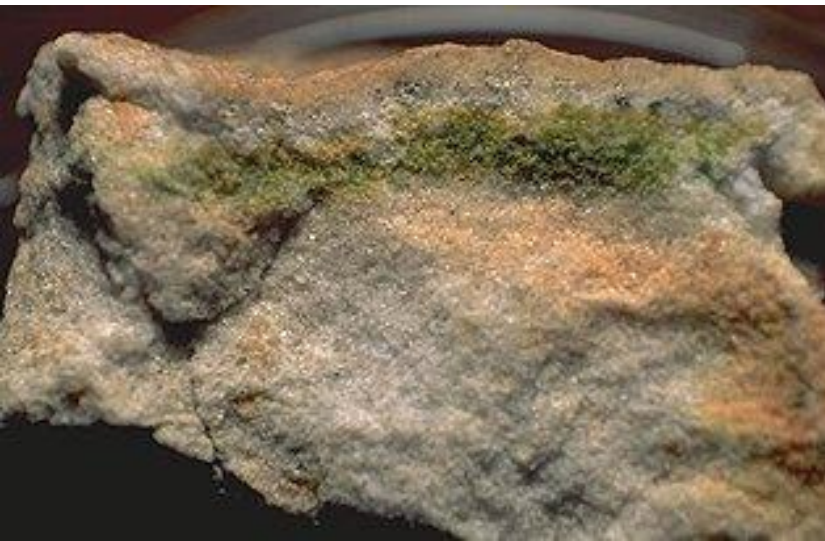
clouds

deep sea sediments

soils



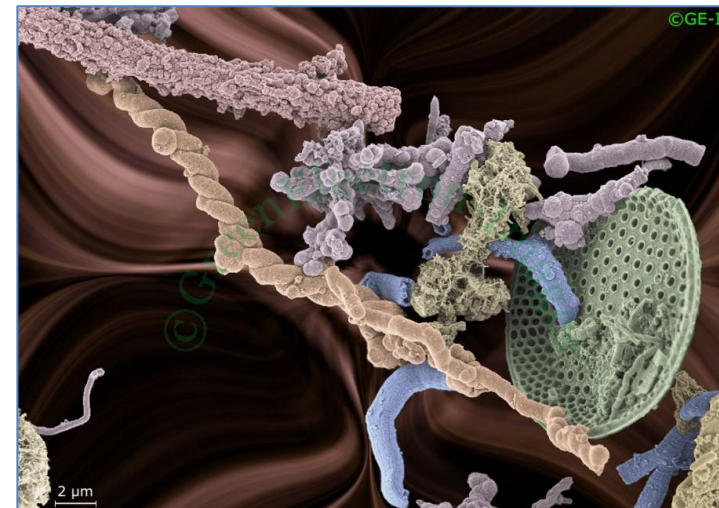
Snow algae on glacier  
Sierra Nevada, CA





# Five Things You Need to Have Life

1. Stable Environment  
be able to adapt to changes
2. Liquid water  
-20°C to 121°C
3. Energy Source  
O<sub>2</sub> and carbohydrates  
oxidant (O<sub>2</sub>) and reductant (sugars)
4. Carbon Source  
carbohydrates  
sometimes different from an energy source
5. Nutrients  
The Biogenic Elements: C, H, N, O, P, S  
Trace Nutrients: Ca, Fe, Cu, Zn, vitamins.....  
some organisms need more than others



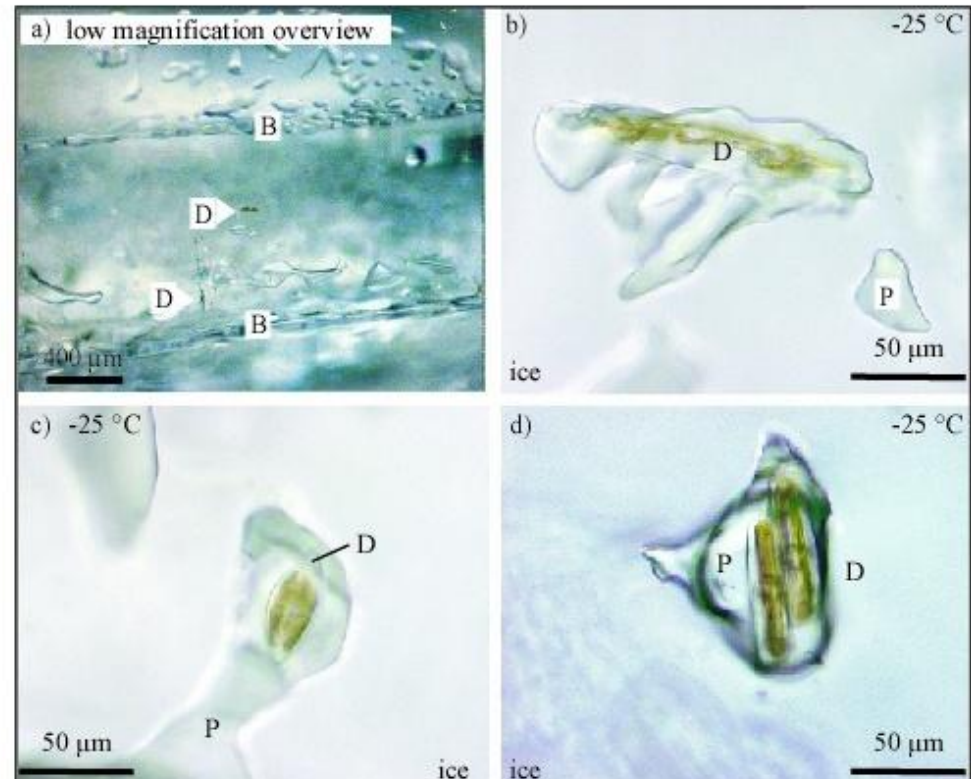
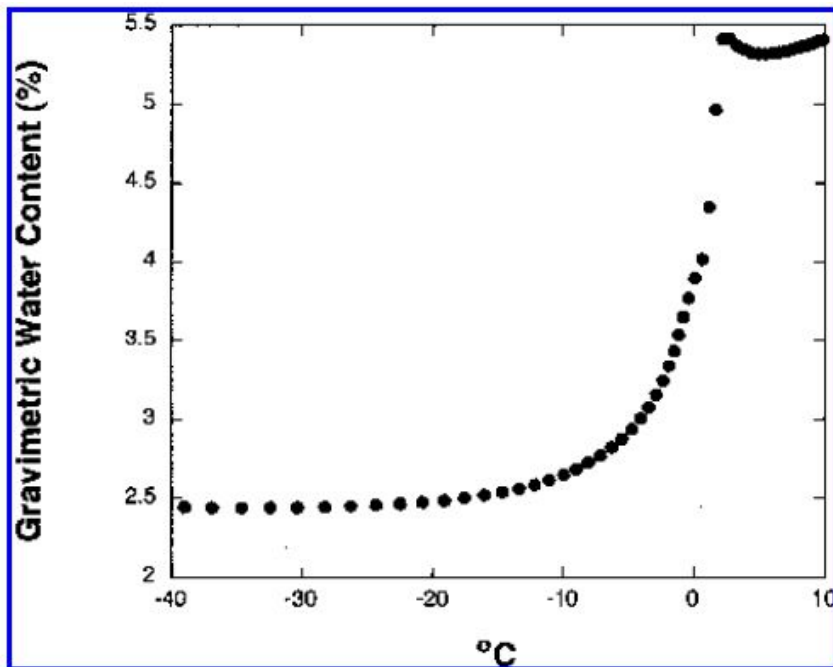
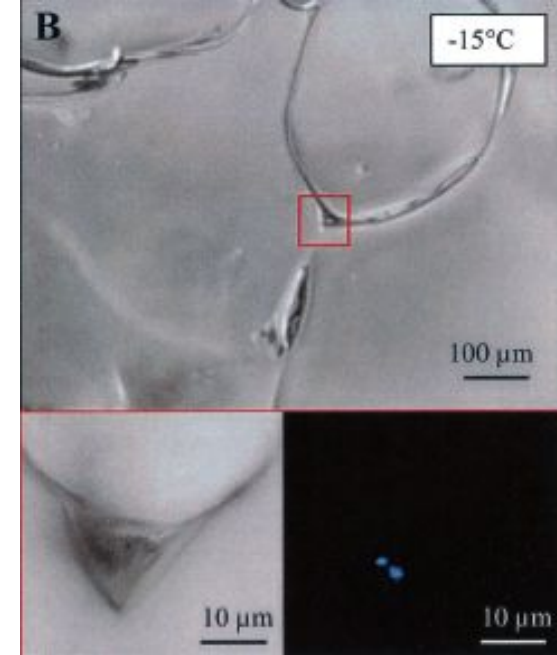


# Liquid Water

If  $T$  below  $0^{\circ}\text{C}$ , microbes can be found growing between ice crystals or in the pore spaces of ice.

Microbes can secrete compounds that can inhibit ice crystal formation.

Soil still contains substantial *thin films* of liquid water below  $0^{\circ}\text{C}$



# Carbon Source

CO<sub>2</sub>      *autotrophs*  
organic carbon      *heterotrophs*

Can combine words for energy and carbon sources:

Name	Energy Source	Carbon Source
<i>Photoheterotroph</i>	Light	Organic C
<i>Photoautotroph</i>	Light	CO <sub>2</sub>
<i>Chemoorganotroph</i>	Organic (reductant) and inorganic chemicals (oxidant)	Organic C
<i>Chemoautotroph</i>	Inorganic chemicals (reductant & oxidant)	CO <sub>2</sub>

# The Importance of Oxygen

Oxygen is a potent source of energy (strongest oxidant available)

Anaerobic metabolisms don't produce as much energy (ATP).

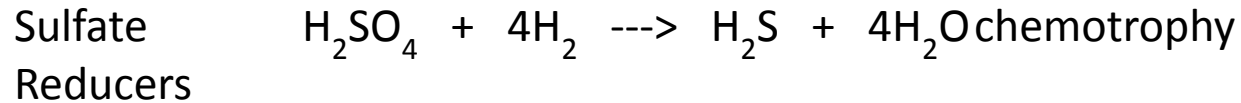
Oxygen is also toxic - it is reactive.

- causes damage to DNA
- causes damage to proteins
- causes damage to lipids
- cells must be able to repair this damage

# Aerobic Metabolisms (*Aerobes*)

Animals	$\text{“CH}_2\text{O”} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$	organotrophy
Manganese Oxidizers	$\text{Mn}^{2+} + \text{O}_2 \rightarrow \text{MnO}_4$ (manganese oxide)	chemotrophy
Iron Oxidizers	$\text{Fe}^{2+} + \text{O}_2 \rightarrow \text{Fe}_2\text{O}_3$ (iron oxide)	chemotrophy
Sulfide Oxidizers	$\text{H}_2\text{S} + \text{O}_2 \rightarrow \text{H}_2\text{SO}_4$ (sulfuric acid)	chemotrophy
Methane Oxidizers	$\text{CH}_4 + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$	chemotrophy
Hydrogen Oxidizers	$2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$	???
Arsenic Oxidizers	$\text{AsO}_3$ (arsenite) + $\text{O}_2 \rightarrow \text{AsO}_4$ (arsenate)	chemotrophy

## Anaerobic Metabolisms (*Anaerobes*)



- a lot of chemical reactions in the environment are catalyzed by microorganisms.
- microbes can carry out some “unusual” reactions to make energy
- energy generation results in constant oxidizing and reducing of compounds: sulfur, iron, manganese, carbon.....
- called *biogeochemical cycling*.



# Temperature

## Temperature

One of the most important environmental factors that affect growth and survival of organisms.

Too hot - proteins *denature* (think: fried egg - unfolded, coagulated)

Too cold - membranes and proteins freeze

For every organism, there is a:

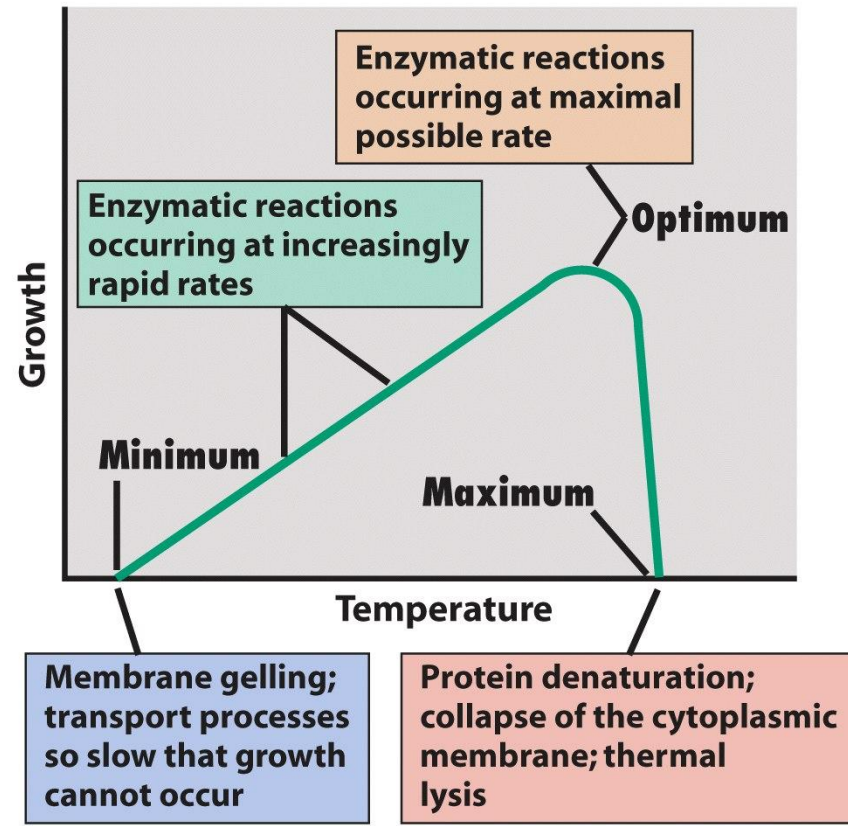
minimum T

optimal T (can be 4 or 105°C)

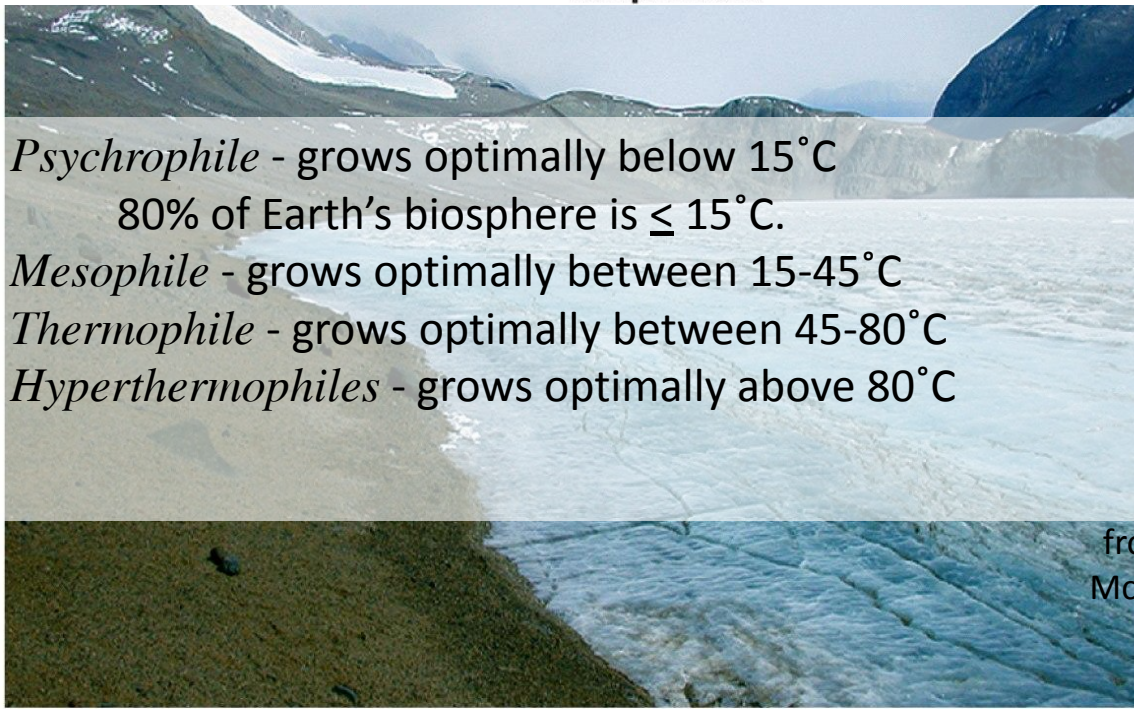
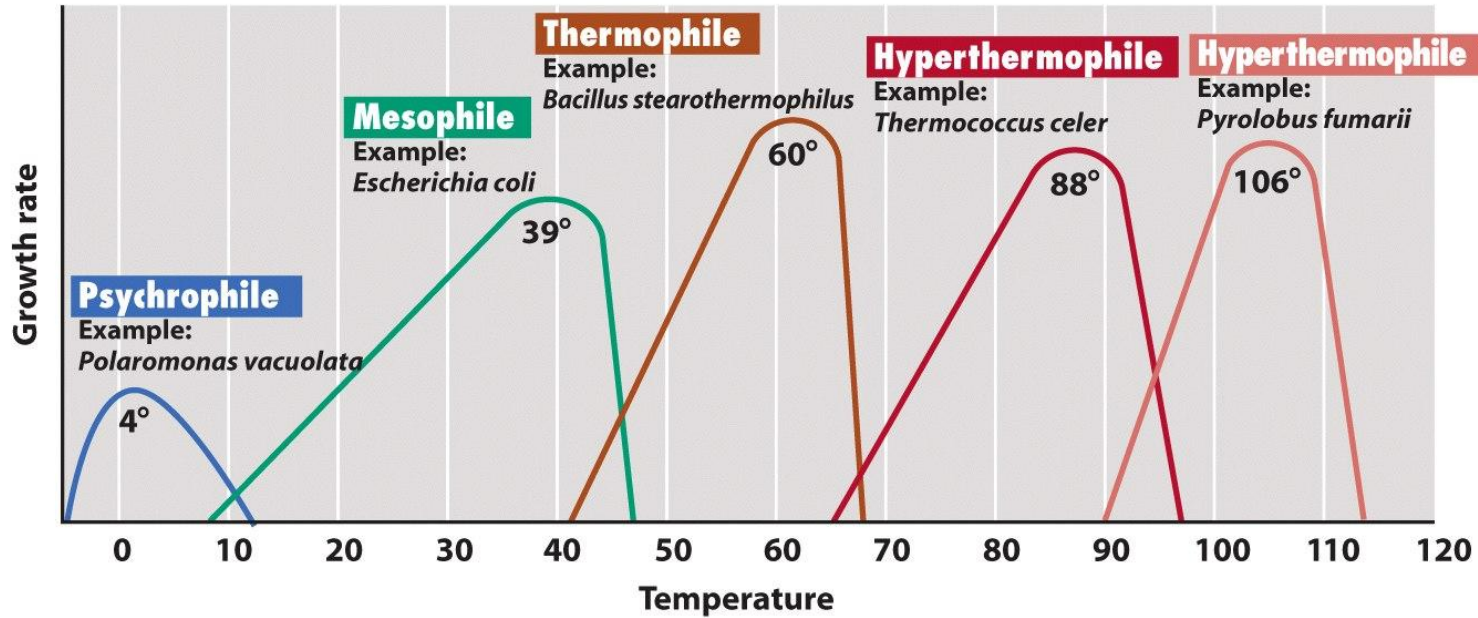
maximum T

(remember water has to be liquid water)

typical range of growth T is 30-40°C



# Growth Temperature

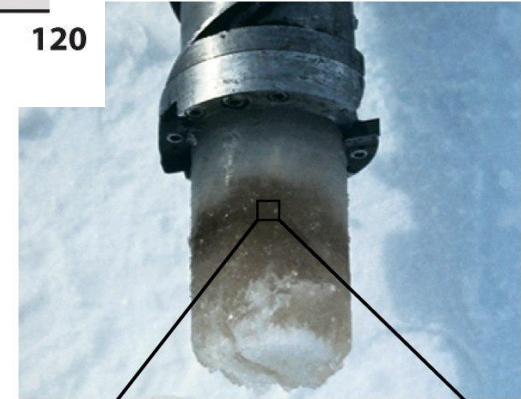


*Psychrophile* - grows optimally below 15°C  
80% of Earth's biosphere is  $\leq 15^\circ\text{C}$ .

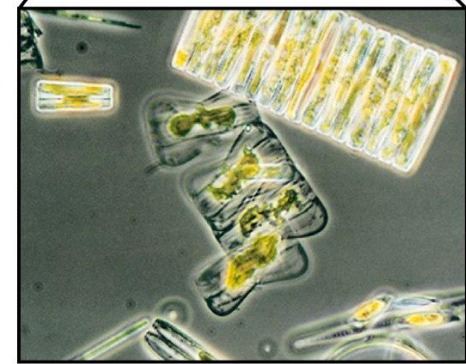
*Mesophile* - grows optimally between 15-45°C

*Thermophile* - grows optimally between 45-80°C

*Hyperthermophiles* - grows optimally above 80°C



(a)



(b)

ice core  
permanently  
frozen seawater  
McMurdo Sound  
Antarctica

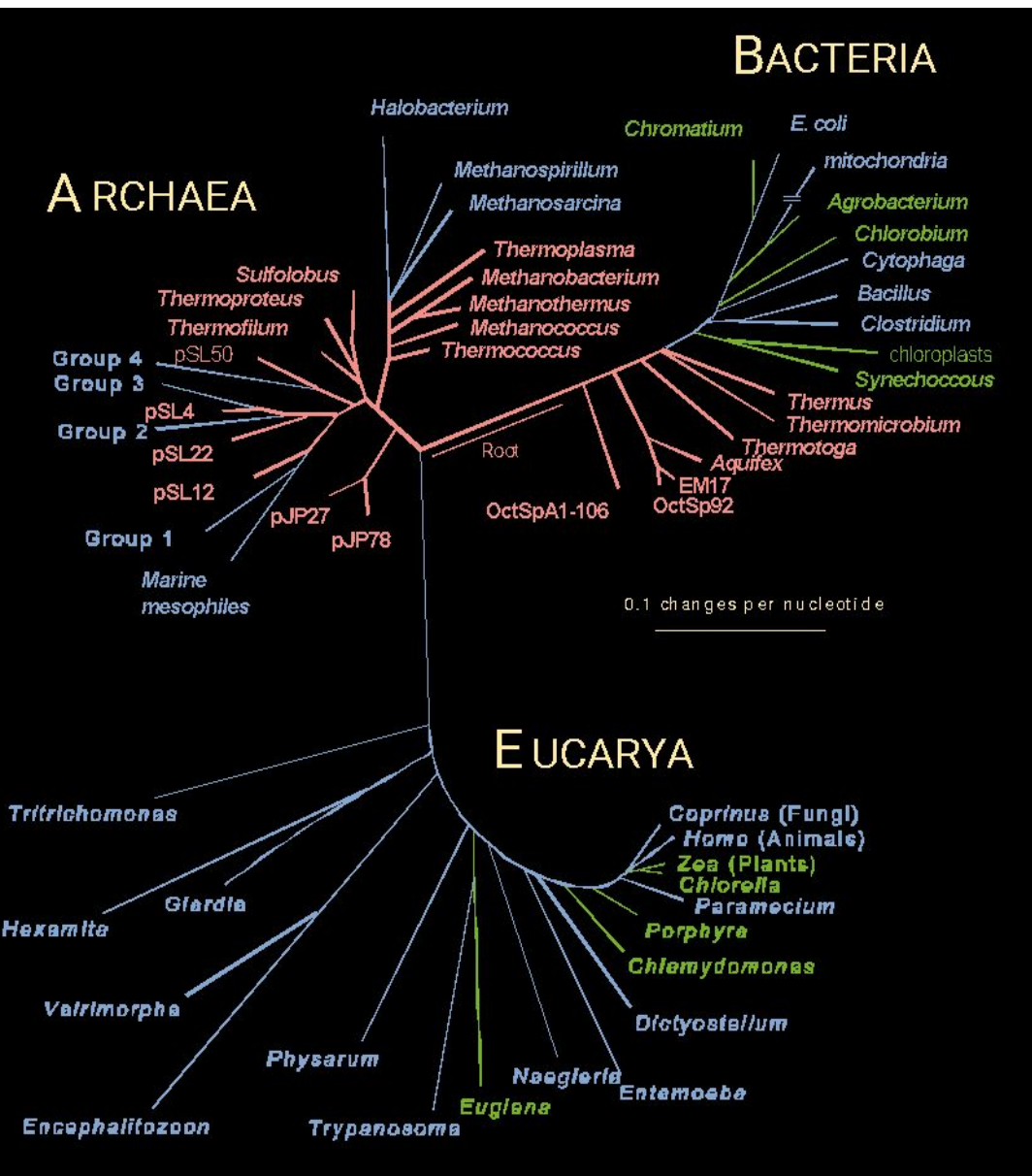
# *Extremophiles*

What is extreme for one organism is necessary for another.  
Organisms are all highly adapted to their *niches*.

*Psychrophile* - grows optimally below 15°C  
80% of Earth's biosphere is  $\leq 15^\circ\text{C}$



# Microbial Life Runs Planet Earth



Microbial diversity is vast.  
 Number of species astronomical.  
 <99.9% of microbial species have  
 been cultured in the lab.  
 Whole new uncultured lineages.  
 Almost nothing known about them.

## Microbes:

turn CO<sub>2</sub> into organic matter  
 most photosynthesis on the  
 planet is done by prokaryotes  
 then turn organic matter back  
 into CO<sub>2</sub>

microbial metabolism is incredibly  
 diverse

## Methane production and oxidation

Metanogens – Archaea – absence of oxygen

Metanotrophs – I and II types – presence of oxygen

Metanotrophs of I type – high amount of methane (e.g. 600 ppm)

Metanotrophs of II type – low amount of methane (ambient or so)

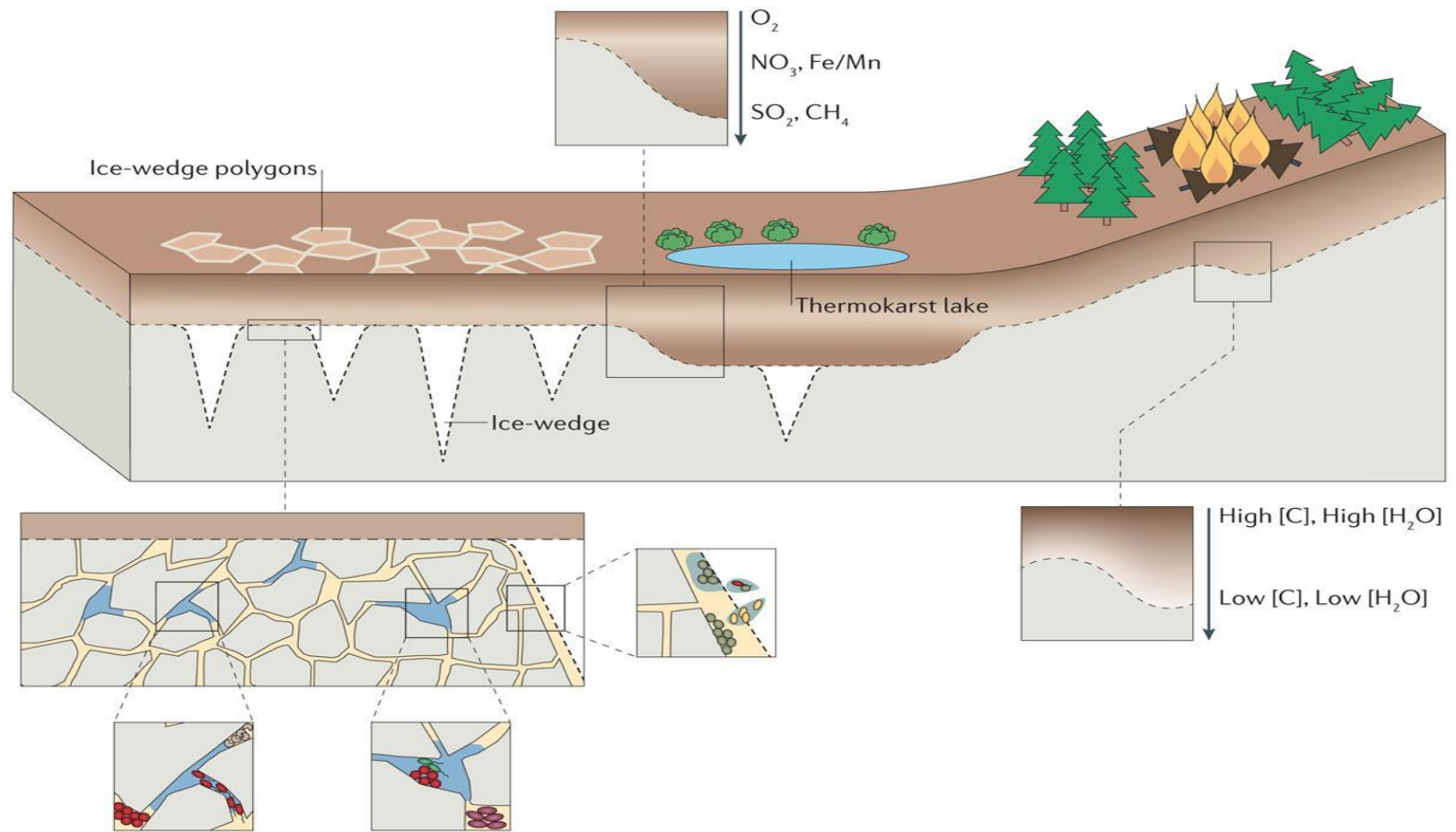
Microbial cultures

Biomarkers (PLFAs, PLELs, alive microbes)

Molecular biology

Fluxes





Nature Reviews | **Microbiology**

The permafrost is overlain by a seasonally thawed active layer (brown). The bold dashed line indicates the surface of the permafrost table. The lowland is characterized by polygons that are separated by ice wedges (white) in the permafrost layer (grey). A thermokarst lake is indicated by a deepening of the active layer and pooling of thaw water at the surface. At high elevations, permafrost thaw results in drainage of the soil moisture and subsidence, which leads to the 'drunken tree' phenomenon. In these locations, permafrost thaw can also originate from the heat that is generated by wildfires. The upper panel and lower right-hand panel indicate differences in redox chemistry, soil and moisture with depth. The lower left-hand panels show close-ups of individual soil microaggregates (brown, active layer; grey, permafrost) and microcolonies of bacterial or archaeal cells in the pores containing free water — that is, brine veins. Figure is not drawn to scale. (Jansson & Tas, Nature Reviews Microbiology (2014) 12, 414–425)

Frozen conditions in permafrost efficiently preserve biological material from DNA to woolly mammoths.

Low water potential, reduced protein flexibility and enzyme activity, limited membrane fluidity, and ice nucleation and melting are all potentially lethal, so it was long assumed that microbes were either dead or dormant when frozen.

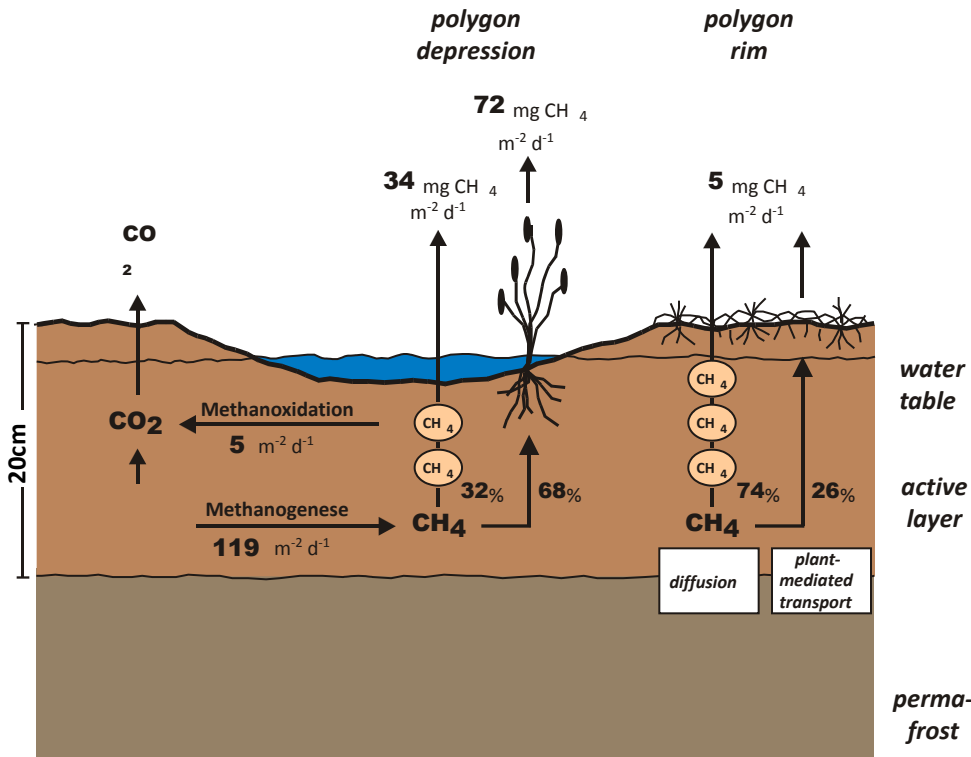
However, high ionic strength within pore water can depress the freezing point and preserve cell viability. Recent experiments demonstrated that permafrost microorganisms remain active at extremely low temperatures (Vishnivetskaya et al., 2006; Gilichinsky and Rivkina, 2011)

Thus, warming could induce SOM decomposition even before permafrost thaws completely. Microbial activity at low temperatures could transform complex organic compounds to soluble metabolites and gases, including the greenhouse gases (GHG): CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O

# Microbial controls on methane fluxes from polygonal tundra

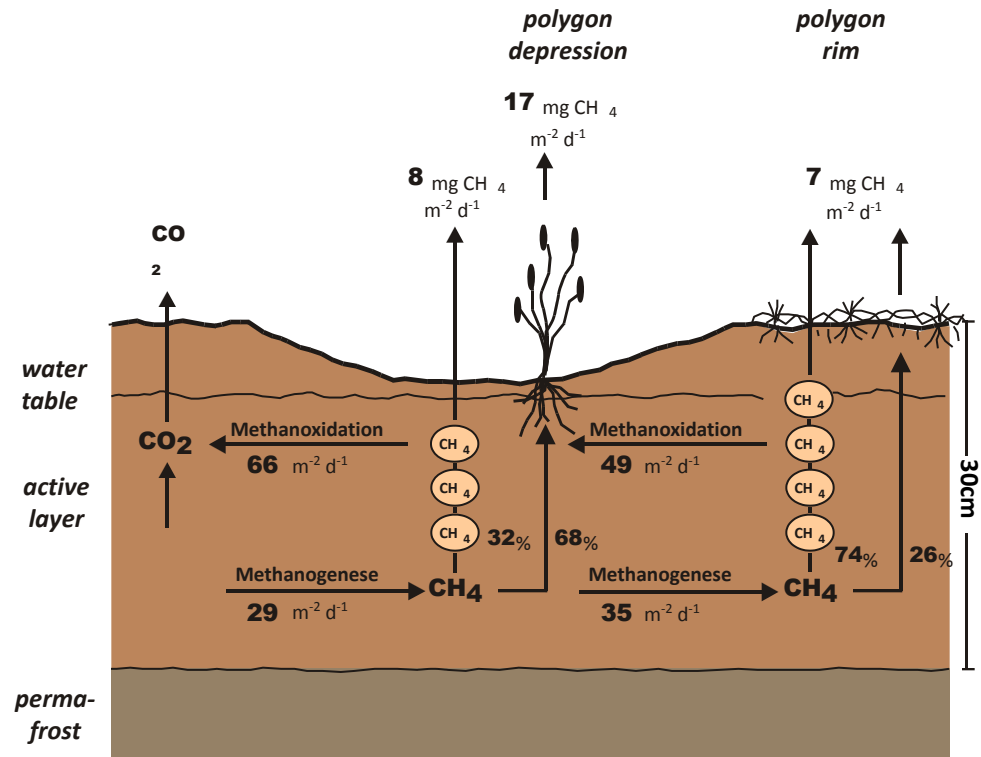
early summer

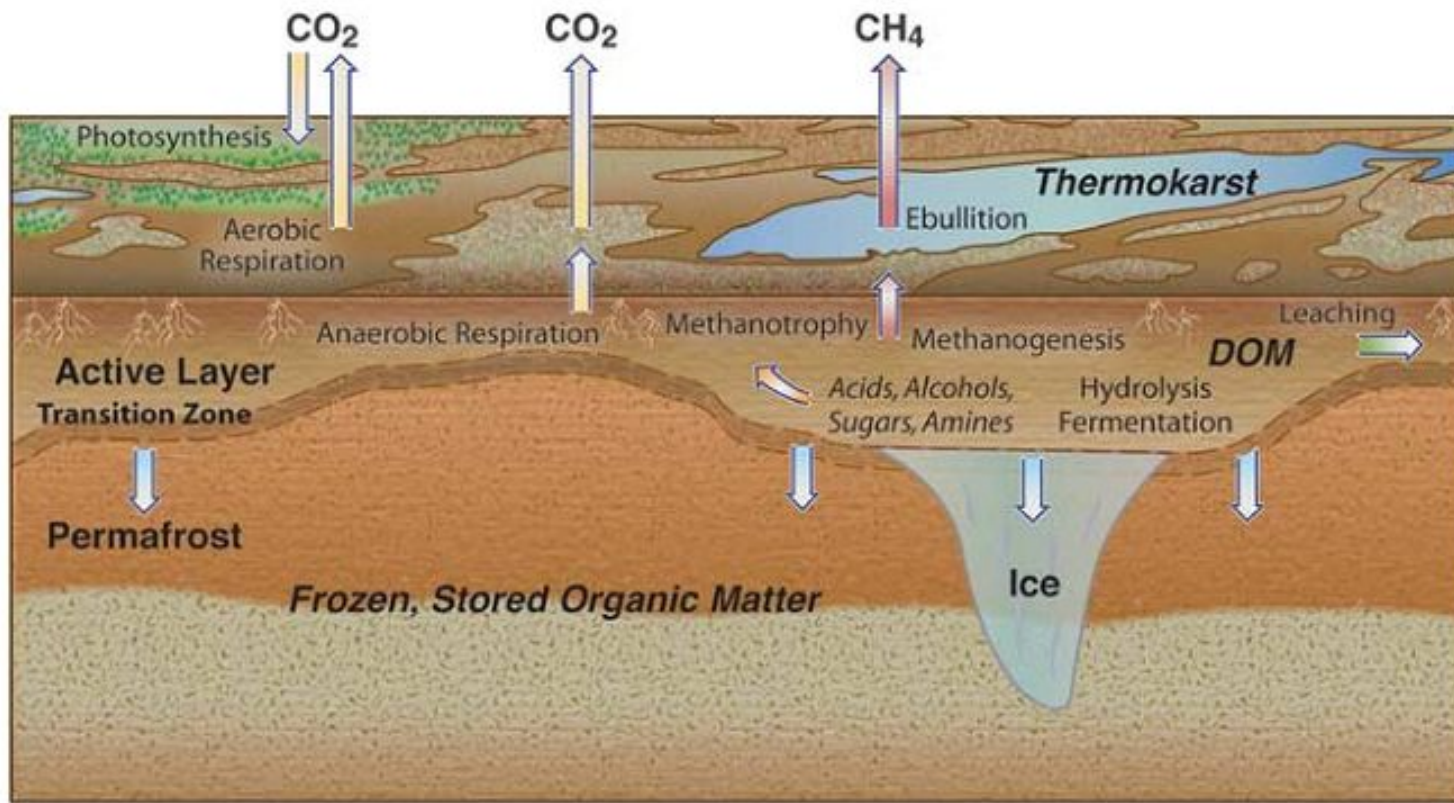
↑ 106 mg CH<sub>4</sub>  
m<sup>-2</sup> d<sup>-1</sup>



late summer

↑ 25 mg CH<sub>4</sub>  
m<sup>-2</sup> d<sup>-1</sup>

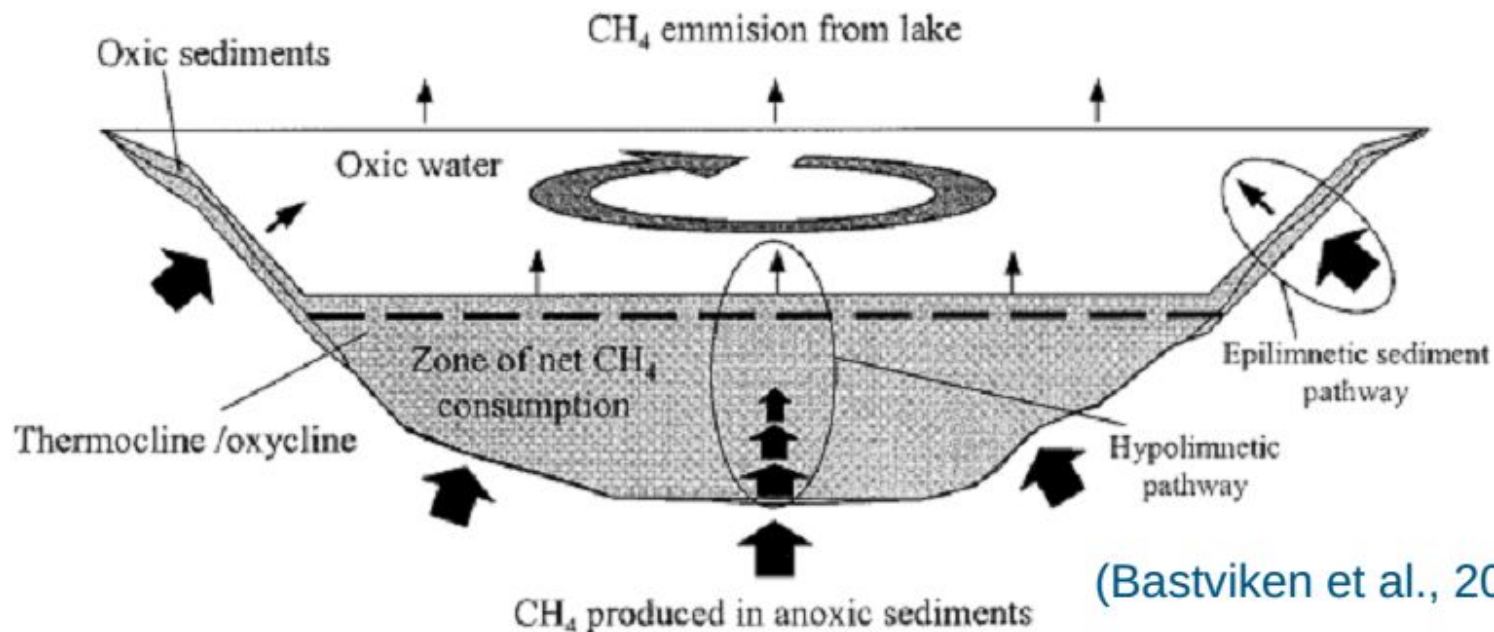




ESD11-015

Key biological processes in the carbon cycle of permafrost environments. Permafrost thawing at the transition zone introduces previously unavailable organic matter into the expanded active layer of soil. Enzymatic hydrolysis decomposes complex organic matter into soluble substrates for microbial fermentation, producing a mixture of organic acids, alcohols and microbial biomass. Methanogenic archaea convert acetate, methylated compounds or  $\text{H}_2$  and  $\text{CO}_2$  into  $\text{CH}_4$  that can be released to the atmosphere through ebullition, diffusion or aerenchyma. Methanotrophs oxidize some of this  $\text{CH}_4$ , converting it to  $\text{CO}_2$ . (Graham et al., The ISME Journal (2011), 1–4)

# Methane transfer in the water body



(Bastviken et al., 2002)

## Перенос метана к поверхности воды

- При пузырьковом выделении метана, пузырьки достигают поверхности воды только на шельфах, **в районах глубин несколько десятков метров**, из-за газообмена с окружающей водой
- При механическом воздействии куски метаногидрата могут отрываться от дна и достигать поверхности воды (Brewer et al. 2002)
- Турбулентная диффузия растворенного метана — эффективный механизм переноса, поскольку окисление метана в океане характеризуется временем жизни 50 лет (Rehder et al. 1999)

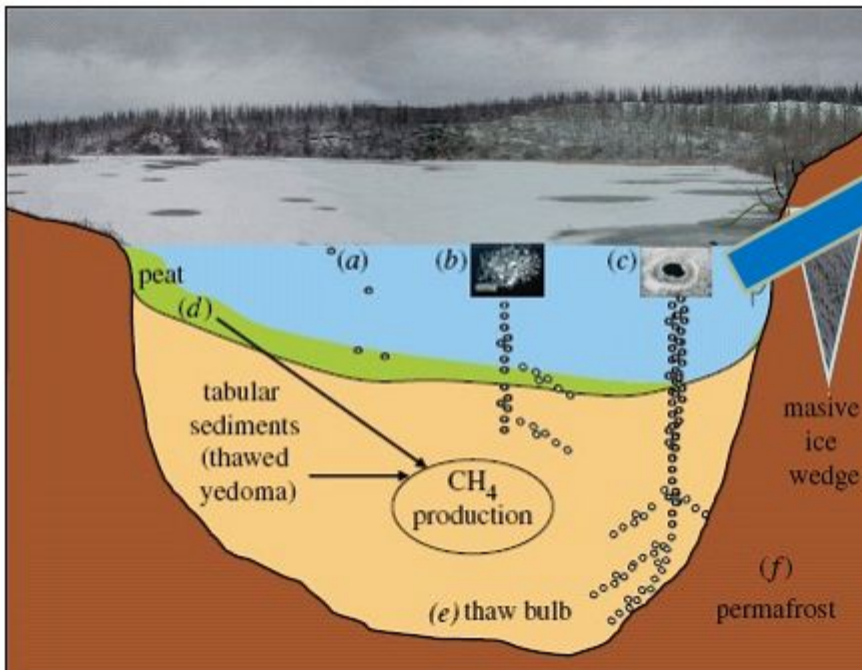




Thermokarst lakes



"hotspot"



## Methane emission: bogs and lakes

Mechanisms of methane production:

On bogs the substrate for methane production comes from surface NPP

In lakes methane is produced (i) from lake bottom NPP and (ii) from the old organics, that has been sequestered in permafrost and comes to positive temperature region while talik is deepening

Implication to annual cycle

On bogs cold season emission is very low

In lakes methane is produced in talik, that is under positive temperatures all year round (40-50% of annual emission happen in cold period)

### Methane production from old organics decomposition

- happens only under positive temperatures
- is exponentially dependent on temperature
- is proportional to decomposable organics content

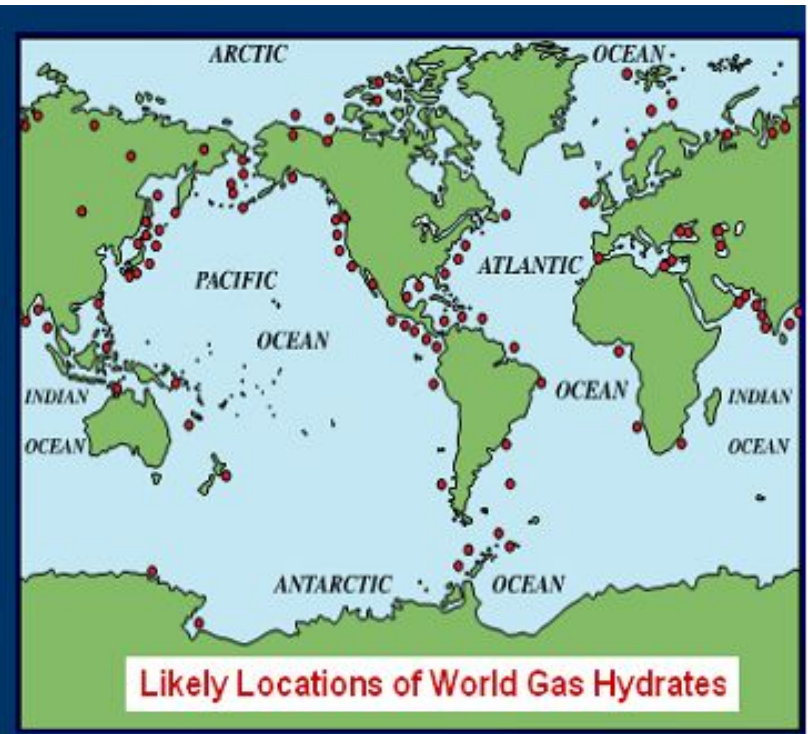
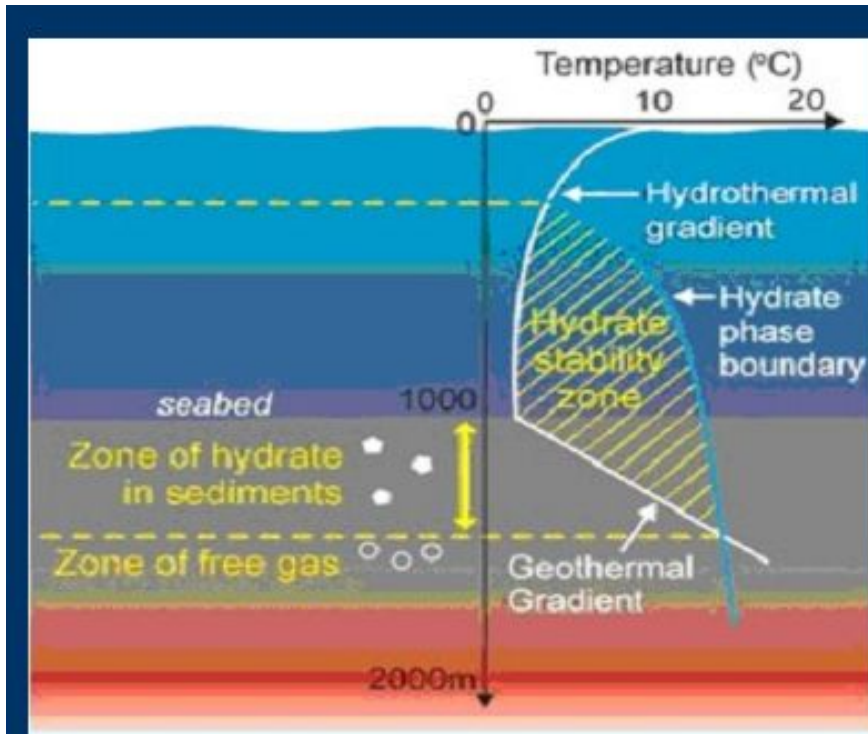
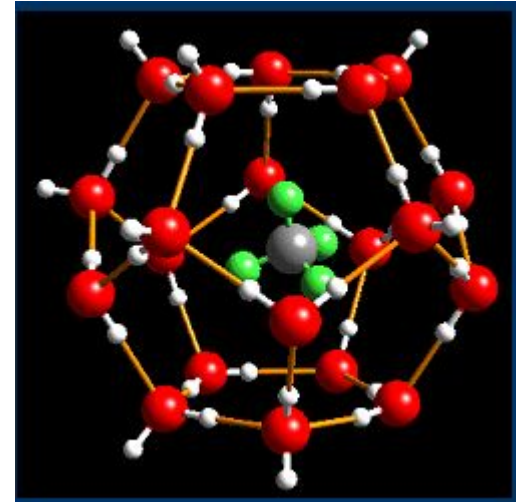
## Methanehydrates

Crystalline structure formed by water molecules with methane molecule inside

Stable for high pressure

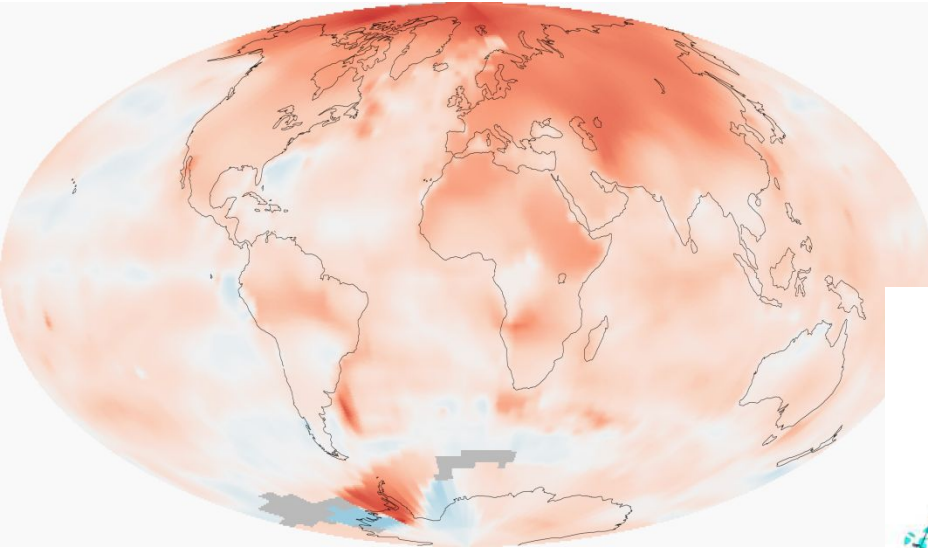
At pressure decreasing and at increasing of temperature disintegrate for  $\text{CH}_4$  and  $\text{H}_2\text{O}$

Density is about  $900 \text{ kg/m}^3$





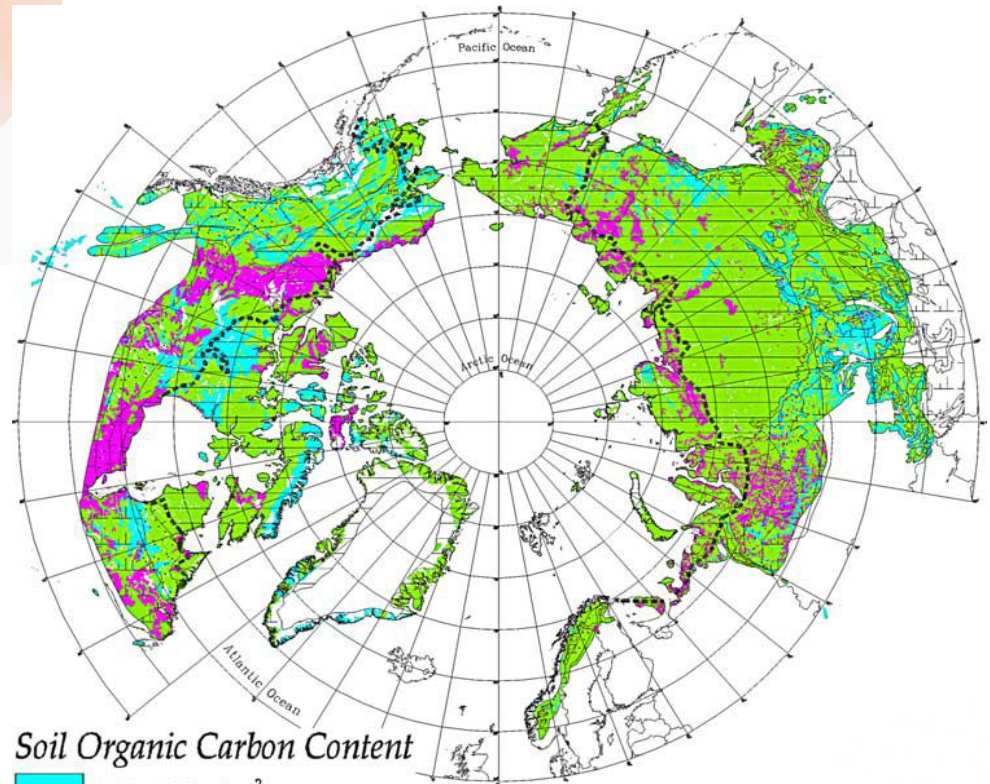
# Temperature anomalies between 2000-2009 compared to average temperatures between 1951-1980



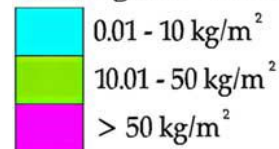
Soil or deposit type	C stocks
Soils 0-300 cm	<b>1024</b>
Yedoma sediments	407
Deltaic deposits	241
<b>Total</b>	<b>1672</b>

Gt =  $10^{15}$ g

## Global carbon pools in the northern circumpolar permafrost region



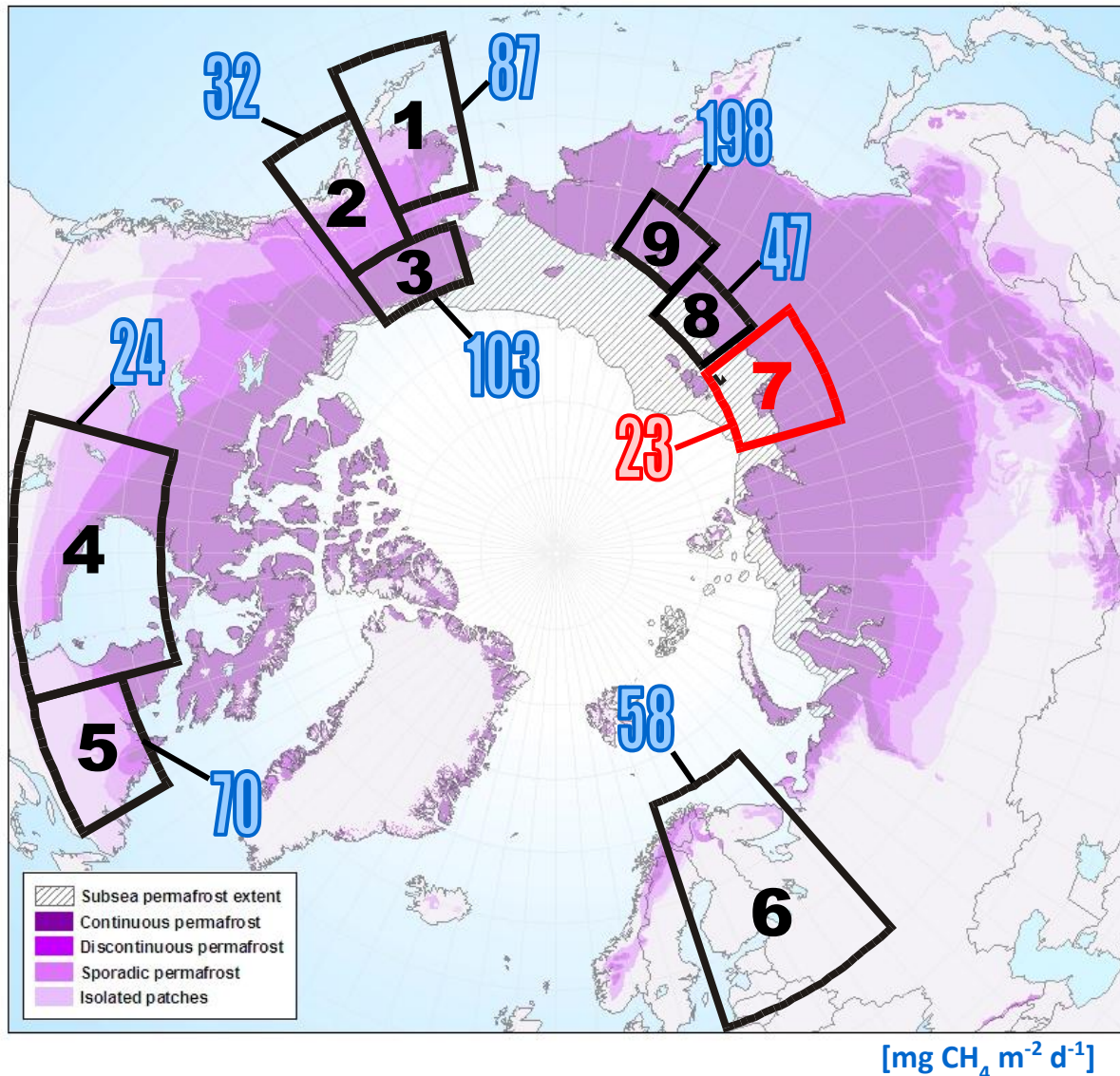
Soil Organic Carbon Content



Tree line

# Circum-Arctic permafrost distribution

## Methane emission from Arctic wetlands



### 1. Yukon Kuskokwim

- Delta
- 2. Central Alaska
- 3. „North Slope“ Alaska
- 4. Hudson Bay Lowlands
- 5. Nouveau Quebec
- 6. Fenno-Soviet Lowlands
- reviewed by Harriss et al. 1993

### 7.

- **Lena-Delt** Wille et al. 2008

### 8. Indigirka

- Lowlands van der Molen et al. 2007

### 9. Kolyma

- Floodplain Conrath et al. 2005

Currently, we cannot predict how microbes will use SOM released by permafrost thawing, or reliably estimate the temperature-dependent activities of the enzymes they produce to degrade this material.

Current biogeochemical models segregate SOM into conceptual pools with different mean residence times (Smith et al., 1997).

If most organic matter trapped in permafrost is difficult to degrade because of its chemical structure (for example, lignin) or its physical structure (for example, particulates or mineral complexes), then this humus comprises a recalcitrant pool that will slowly stimulate microbial growth and GHG production.

Alternatively, if plant litter was rapidly frozen in permafrost, then microbes could quickly metabolize thawed polymers like cellulose or protein.

Increased temperature may also cause changes in protein structure and conformation, protein adsorption, altered protein expression and shifts in microbial populations, which are not currently modeled (Waldrop et al., 2010; Wallenstein et al., 2011). We might expect soil warming to select for microbes producing enzymes that degrade SOM more efficiently at higher temperatures.



Predictions of soil GHG flux include increasingly sophisticated representations of processes in the subsurface carbon cycle , but these models are poorly parameterized for permafrost regions (Riley et al., 2011).

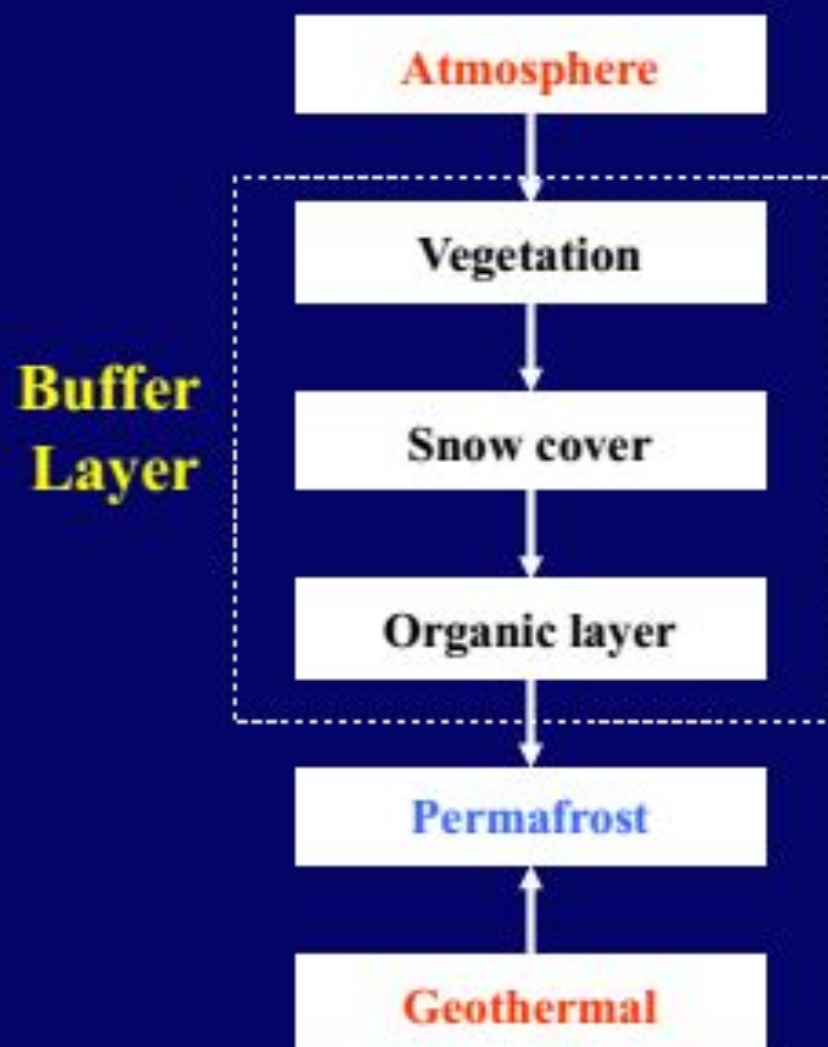
16S rRNA gene sequence data have identified both hydrogenotrophic and acetotrophic (methylotrophic) methanogen phylotypes in Arctic tundra samples, at substantial abundance (Wagner and Liebner, 2010).

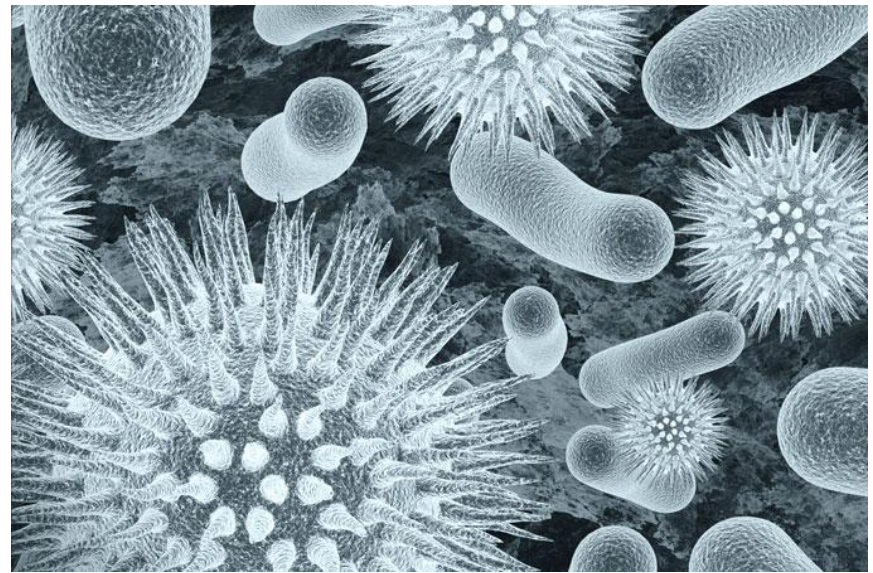
The two groups of methanogens differ in their substrates, syntrophic associations and isotopic fractionation of carbon: it is important to distinguish between the methanogenic pathways to predict the proportions of CH<sub>4</sub> and CO<sub>2</sub>, as well as fluxes (Walter et al., 2008).

Changes in methanogen abundance could also confuse estimates of the temperature and pH response factors.

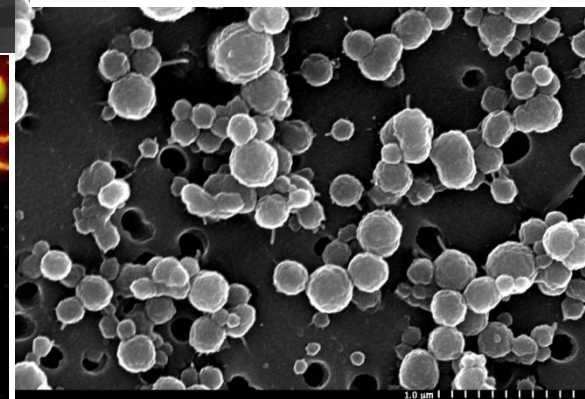
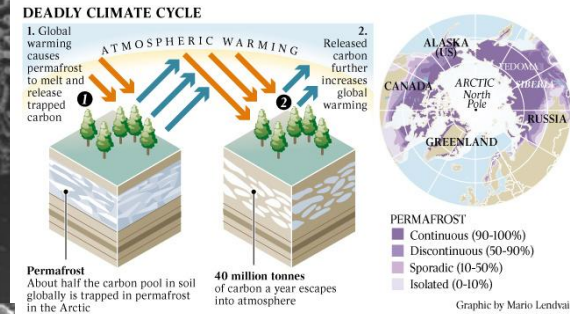
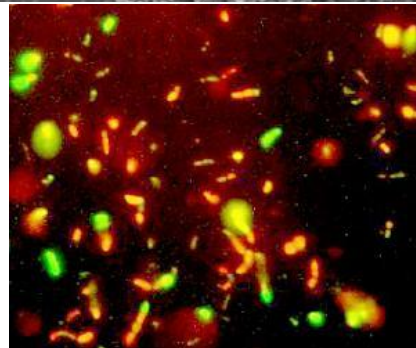
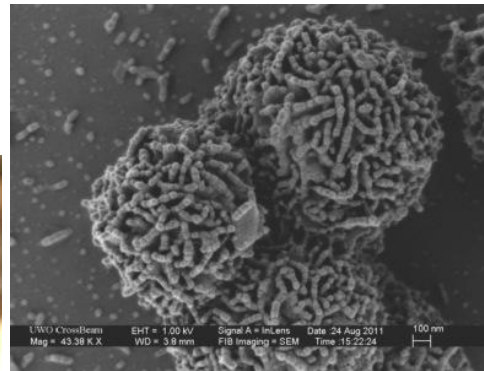
Eventually, microbial activities will dictate whether permafrost environments will be a net source or sink of GHG in the coming decades and whether large-scale feedbacks to regional and global climate will develop because of increased CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> emissions and vegetation changes in the Arctic.

# What Drives Permafrost Formation?





**Thank you for your attention!**



Field school-seminar for young scientists on polar research  
September 18—23, 2016, Field station of AARI "Ladoga"



- В [определении терминов Четвертого оценочного доклада IPCC](#), "время жизни" имеет несколько значений. Наиболее подходящим является:
- "Время обращения (Т) (также называемое глобальным временем жизни в атмосфере) это отношение массы вещества в хранилище (например, газового компонента в атмосфере) к общей скорости удаления из хранилища  $S: T = M / S$ . Для каждого процесса удаления может быть определено свое время обращения. В биологии почв это называется средним временем пребывания." Другими словами, время жизни - это среднее время, которое индивидуальная частица проводит в данном блоке. Оно определяется как размер блока (хранилища) деленный на общую скорость потока частиц в хранилище или из него. [Раздел 4.1.4 Третьего оценочного доклада IPCC](#) говорит об этом более подробно.
- В схеме углеродного цикла, приведенной выше, есть два набора чисел. Черные представляют размеры блоков в гигатоннах углерода (Гт). Фиолетовые означают потоки (или скорости потоков) в блок или из него в гигатоннах в год (Гт/год).
- Небольшой подсчет показывает, что около 200 Гт углерода покидает атмосферу и входит в нее каждый год. Следовательно, в первом приближении при размере блока 750 Гт можно получить время жизни молекулы CO<sub>2</sub>  $750 \text{ Гт} / 200 \text{ Гт в год} =$  примерно 3-4 года. (Впрочем, более точный подсчет прихода и ухода показывает общий дисбаланс; углерод в атмосфере растет на примерно 3,3 Гт в год).
- Верно, что конкретная молекула CO<sub>2</sub> имеет короткое время пребывания в атмосфере. Однако в большинстве случаев, покидая атмосферу, она просто меняется местами с другой молекулой в океане. То есть потенциал потепления от CO<sub>2</sub> не имеет отношения к времени жизни CO<sub>2</sub>.
- В действительности потенциал потепления определяется тем, как долго избыточный CO<sub>2</sub> будет оставаться в атмосфере. CO<sub>2</sub> химически инертен и удаляется только за счет биопоглощения и [растворения в океане](#). Биопоглощение (за исключением образования ископаемого топлива) является углеродно нейтральным: любое растущее дерево когда-нибудь умрет и разложится, освобождая CO<sub>2</sub>. (Да, возможен некоторый выигрыш за счет восстановления лесов, но он, по всей вероятности, невелик по сравнению с эмиссией от ископаемого топлива).
- Растворение CO<sub>2</sub> в океане происходит быстро, но дело в том, что поверхностный слой океана уже "наполнен", и таким образом, узким местом является перенос углерода в глубину. Этот перенос в основном осуществляется медленной циркуляцией с оборотом слоев океана (\*3). Такой оборот занимает 500-1000 лет. Следовательно, временной масштаб потенциала потепления от CO<sub>2</sub> не менее 500 лет является вполне обоснованным (См. [Четвертый оценочный доклад IPCC раздел 2.10](#)).

- Источниками углекислого газа в атмосфере Земли являются вулканические выбросы, жизнедеятельность биосферы, деятельность человека. Антропогенными источниками являются: сжигание ископаемого топлива; сжигание биомассы, включая сведение лесов; некоторые промышленные процессы приводят к значительному выделению углекислоты (например, производство цемента). Основными потребителями углекислого газа являются растения, однако, в состоянии равновесия, большинство биоценозов за счет гниения биомассы производит приблизительно столько же углекислого газа, сколько и поглощает. Антропогенная эмиссия увеличивает концентрацию углекислого газа в атмосфере, что, предположительно, является главным фактором изменения климата. Углекислый газ является "долго живущим" в атмосфере. Согласно современным научным представлениям, возможность дальнейшего накопления CO<sub>2</sub> в атмосфере ограничена риском неприемлемых последствий для биосферы и человеческой цивилизации, в связи с чем его будущий эмиссионный бюджет является конечной величиной.