EPFL

Science of Climate Change

Polar Climate Change and Arctic Amplification

Exercise session #12

Overview of todays class

Starting with:

Sea ice loss calculation

Moving on to:

- Polar climate change
- Arctic amplification
  - Feedback mechanisms in winter
    - Cloud and water vapour
    - Albedo
    - CO_2 and anthropogenic emissions
  - Feedback mechanisms in summer
    - Ocean
    - Lapse rate
    - Atmospheric transport
    - Planck
- Low and High cloud feedback in the Arctic

Ice loss in Switzerland and the Arctic

How long would it take, if we used the annual average energy that the Arctic ocean absorbed in addition due to sea ice retreat between 1980 and 2020 to melt the remaining glacier volume in Switzlerand?

- Hint 1:
  - Enthalpy of melt: 334 kJ / kg
  - Density of ice: 900 kg/m^3
  - Albedo of ice: 0.85
  - Albedo of ocean: 0.07

Hint 2 : Information needed:

- Incoming radiation over the arctic (W/m^2)
- New albedo taking into account ice receeding
- Glacier volume Switzerland
- Area of ice melted/area of open ocean created

Ice loss in Switzerland and the Arctic

How long *would it take, if we used the annual average energy that the Arctic* ***ocean absorbed*** *in addition due to* ***sea ice retreat*** *between 1980 and 2020 to melt the remaining glacier volume in Switzlerand?*

Enthalpy of melt: 334 kJ / kg
Density of ice: 900 kg/m³
Albedo of ice: 0.85
Albedo of ocean: 0.07

Start with the difference in energy absorption

Calculate albedo difference

$0.85 - 0.07 = 0.78$

Convert into absorbed solar radiation

Annual solar radiation over arctic = $80\ W/m^2$

$1.65 \times 10^{13}\ m^2 \times 80\ W/m^2 \times 0.78 = 1.03 \times 10^{14}\ W$

Calculate additional open ocean area

Sea ice extent in 1980 = $15.4 \times 10^{13}\ m^2$

Sea ice extent in 2020 = $13.75 \times 10^{13}\ m^2$

"New " open ocean area = $15.4 - 13.75 = 1.65 \times 10^{13}\ m^2$

Calculate remaining mass of glaciers in CH

Glacier volume remaining = $53\ km^3$ / $53\text{x}10^9\ m^3$

Mass = density x volume = $(900\ kg/m^3) \times (53\text{x}10^9\ m^3)$

Mass = 4.77×10^{13} kg

Total energy required to melt this mass

Enthalpy is energy required to do work. So enthalpy of melt is the energy need to put in to melt one kg of ice.

Energy = $(4.77 \times 10^{13}\ kg) \times (334\ kJ/kg) = 1.59 \times 10^{19}\ J$

Calculate time to melt this

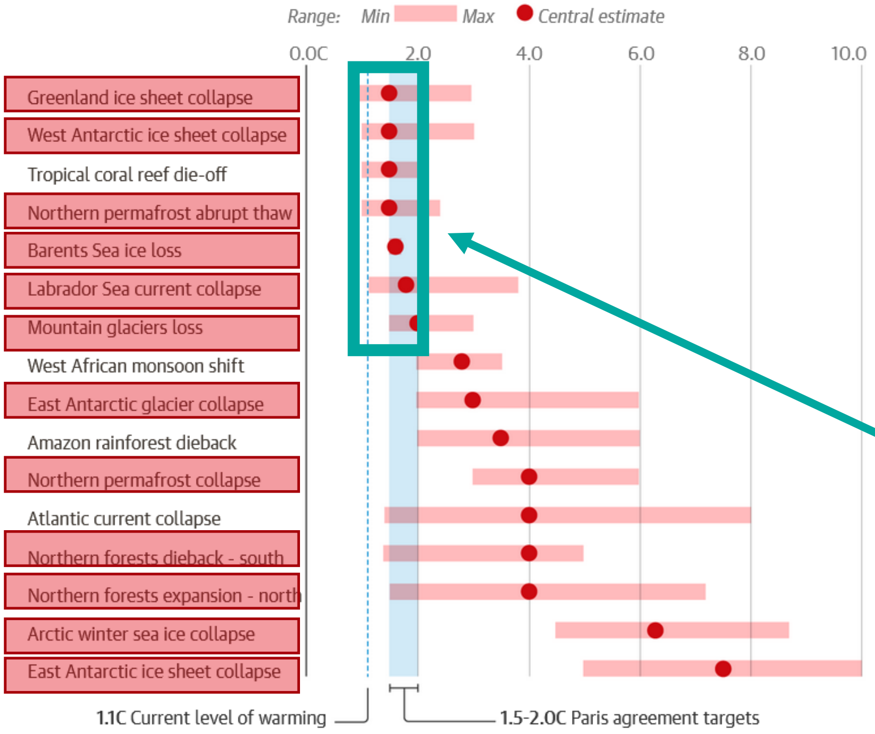
Note: A Watt is a **Joule per second**

Time (seconds) = $(1.59 \times 10^{19}\ J) / (1.03 \times 10^{14}\ W)$ =

1.55×10^5 seconds

Regional Climate – Polar Climate Change

12 out of 16 top tipping points are associated to extreme environments (polar and high altitude regions)



Guardian graphic. Source: Armstrong McKay et al, Science, 2022. Note: Current global heating temperature rise 1.1C
Paris agreement targets 1.5-2.0C

Tipping point is defined as a critical threshold in the Earth's climate system that, when crossed, can lead to large, irreversible changes.

6 out of 7 tipping points potentially activated within the Paris agreement temp range targets are related to polar regions and the cryosphere

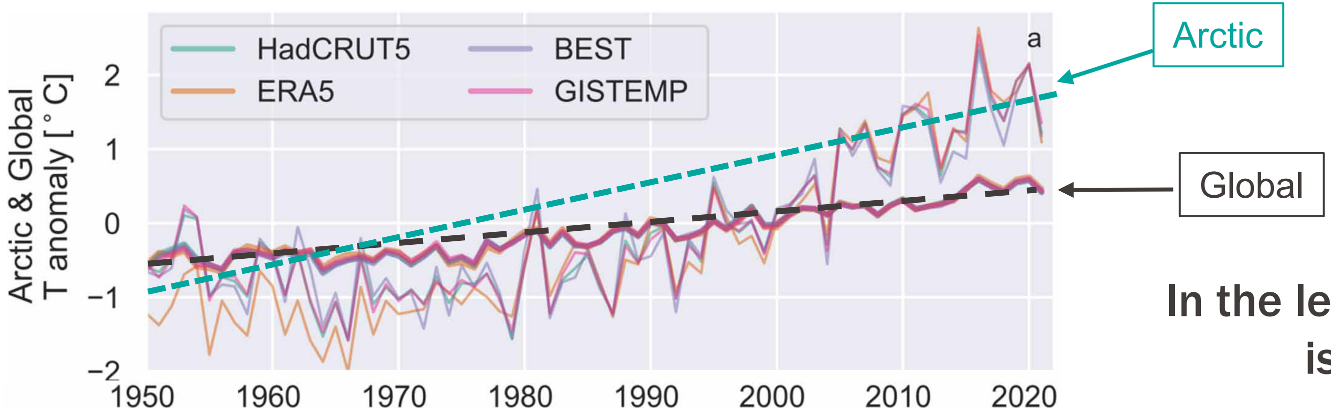
Why is this?

Polar Amplification

Arctic Amplification

....the phenomenon where the Arctic warms faster than the rest of the planet due to climate change

→ Due to the effect of multiple feedback mechanisms which collectively lead to an amplified climate change effect



In the lecture you saw that there is more Arctic warming in Winter – why is this?

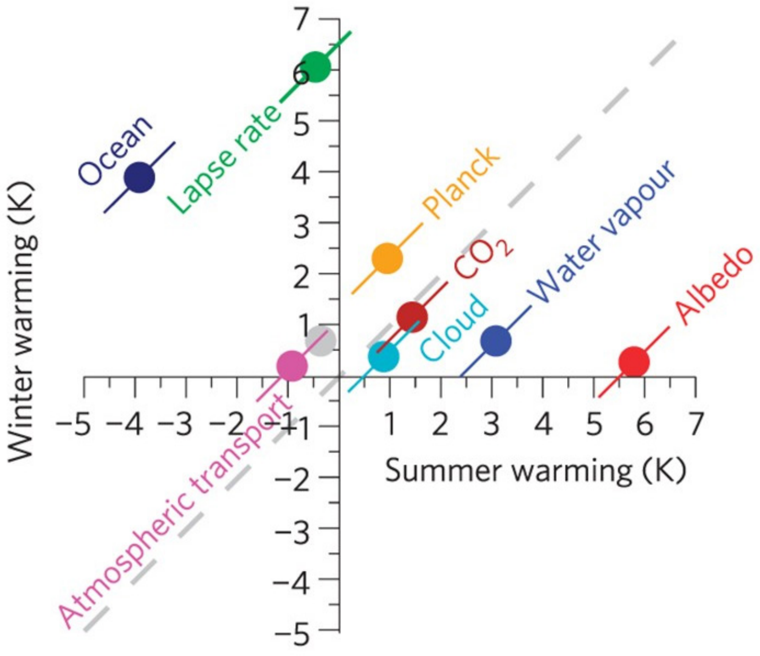
Arctic warming is stronger in winter (December–February, DJF) than summer (June–August, JJA; Fig. 1b). The strong winter warming has been linked to the release of heat stored in the ocean and to increases in downwelling longwave radiation[26], but a quantitative understanding of the seasonal cycle of individual feedback mechanisms is lacking.

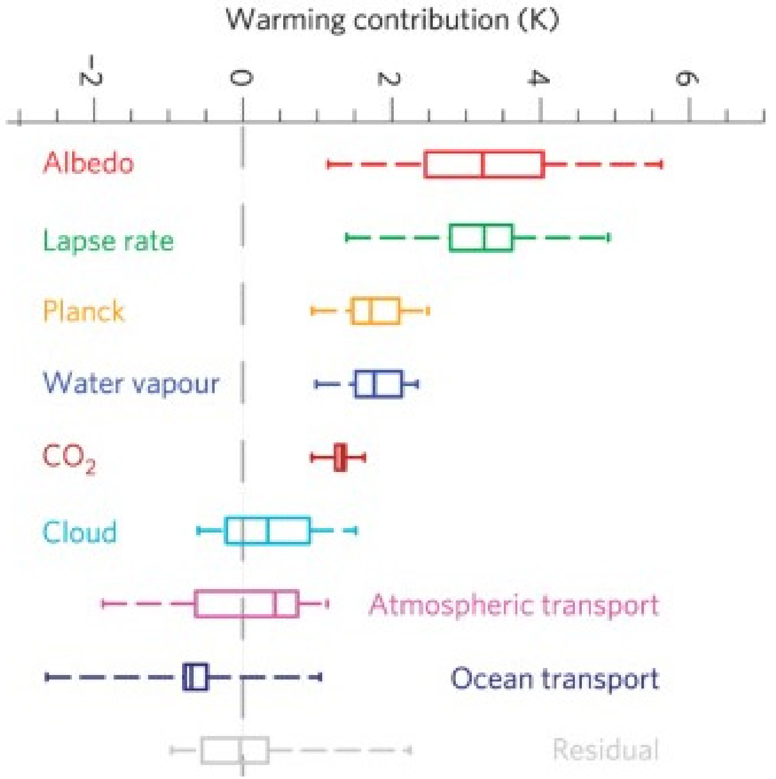
**Pithan and Mauritsen, Nat. Geoscience, 2014*

Arctic Amplification

Warming contributions of individual feedback mechanisms. Winter vs Summer warming

*Pithan and Mauritsen, Nat. Geoscience, 2014

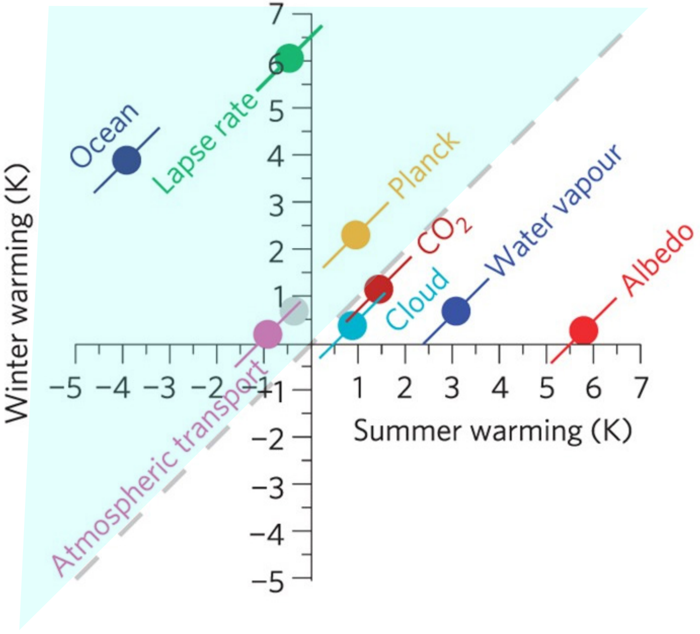




Arctic Amplification

Warming contributions of individual feedback mechanisms. Winter vs Summer warming

*Pithan and Mauritsen, Nat. Geoscience, 2014



Winter warming

Ocean

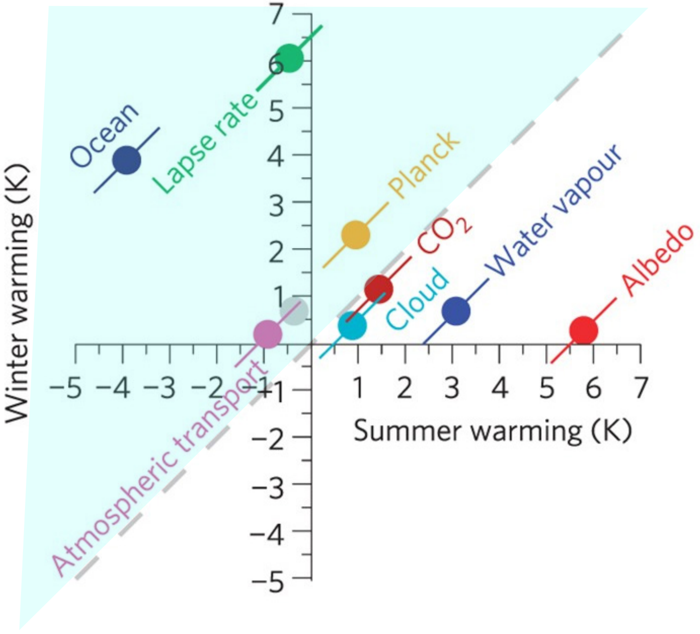
In winter, solar radiation is minimal so the ocean becomes a significant source of heat which it releases as stored energy into the atmosphere. Where the ocean is ice free this will occur through latent and sensible heat fluxes.

This release of heat makes the lower atmosphere in winter warmer than it would have been otherwise and contributes to reduced sea ice growth during winter further contributing to warming.

Arctic Amplification

Warming contributions of individual feedback mechanisms. Winter vs Summer warming

*Pithan and Mauritsen, Nat. Geoscience, 2014



Winter warming

Lapse rate

Remember: Lapse rate is the rate at which the atmospheric temperature decreases with altitude.

The lapse rate feedback refers to the **temperature gradient between the surface and the atmosphere changes in response to the surface warming.**

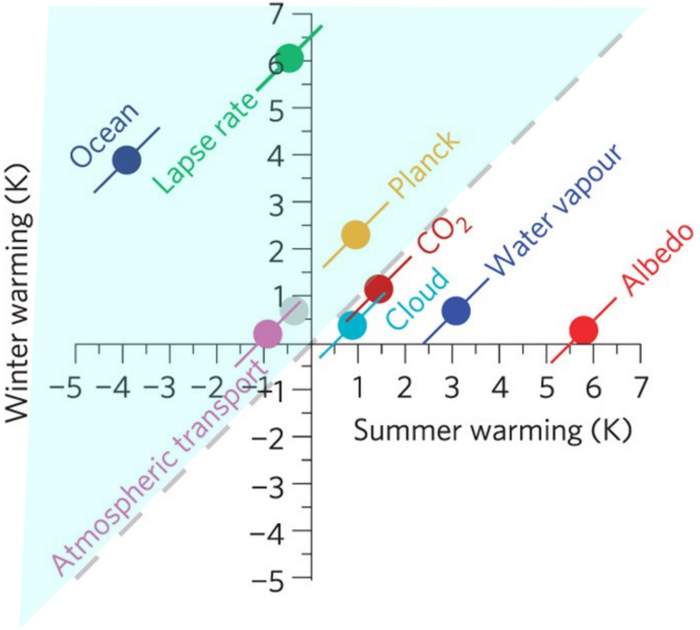
The lapse rate feedback is stronger in winter because of strong temperature inversions where the surface is **much** colder than the air above it leading to a steeper lapse rate.

→ This leads to a stable lower atmosphere and this inhibits the exchange of air masses and therefore heat between the atmospheric layers.

Arctic Amplification

Warming contributions of individual feedback mechanisms. Winter vs Summer warming

*Pithan and Mauritsen, Nat. Geoscience, 2014



Remember: Lapse rate is the rate at which the atmospheric temperature decreases with altitude.

Winter warming

Lapse rate

However, with warmer winter surface temperatures, the surface inversions will be weaker which decreases the steepness of lapse rate gradient.

This does not mean that the gradient becomes flat or reverses however!

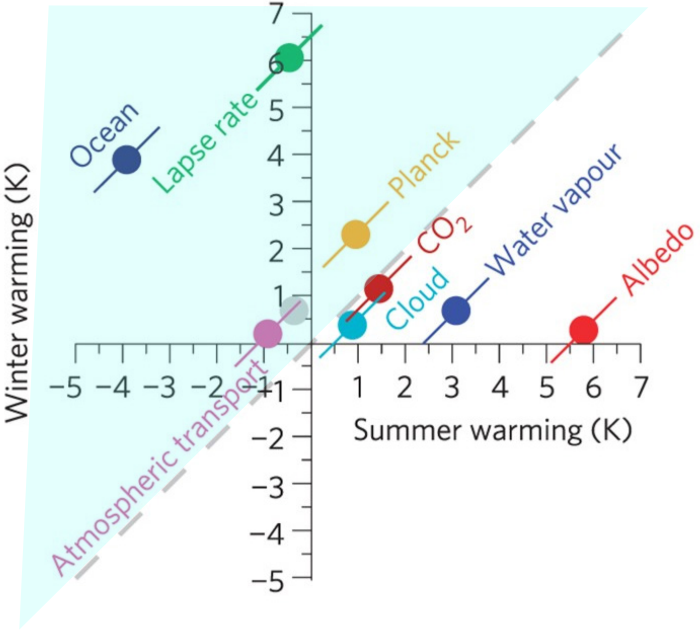
→ Even with significant warming the lapse rate for Earths atmosphere will remain positive!

Due to the weakening of the lapse rate gradient, (i.e by definition the rate of loss of temp with altitude will be less), the temperature difference driving the heat transfer process as a function of altitude between surface and upper atmosphere is reduced.

→This added inefficiency in heat loss creates a positive feedback further increasing the surface temperature, amplifying warming further.

Arctic Amplification

Warming contributions of individual feedback mechanisms. Winter vs Summer warming



Winter warming

Atmospheric transport

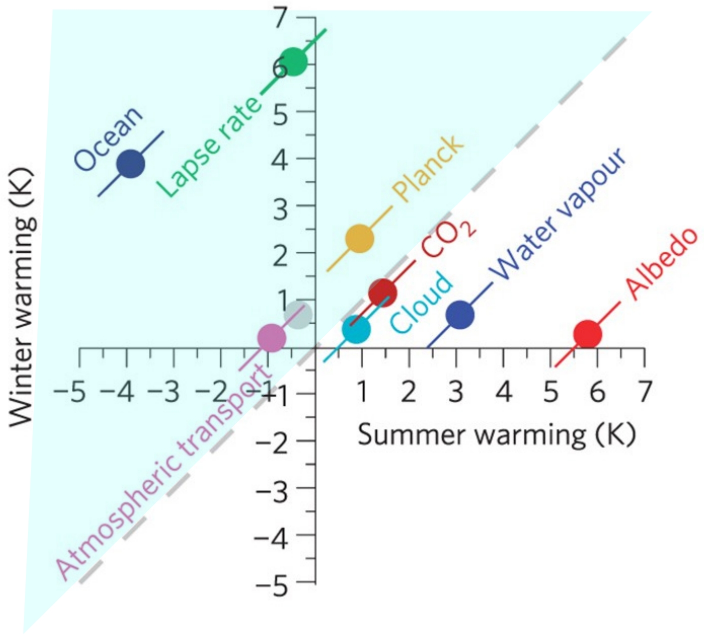
As the Arctic warms there are increased transport of warmer air masses from lower latitudes due to changes in atmospheric circulation patterns such as the jet stream.

Increased warm air mass transport increases surface temperatures and reduces the formation of sea ice and causes the existing sea ice to melt,

→ further exposing the ocean which releases more heat to the atmosphere – **positive feedback loop.**

Arctic Amplification

Warming contributions of individual feedback mechanisms. Winter vs Summer warming



Winter warming

Planck

Planck feedback refers to **how the Earth's surface and atmosphere radiate heat in response to changing temperature.**

$$LWR = \varepsilon * \sigma T_e^4$$

Where LWR = longwave radiation or radiation emitted by Earth
ε = surface emissivity

Note that outgoing LWR is a function of temperature to the power of 4 !
→ this means that colder surfaces will radiate disproportionately lower energy than warmer ones.

Planck Feedback

Black body radiation is said to be thermal radiation such that the higher the temperature of a body the more radiation it emits at every wavelength.

→ This is a negative feedback as the surface is warming then leading to a cooling of the atmosphere.

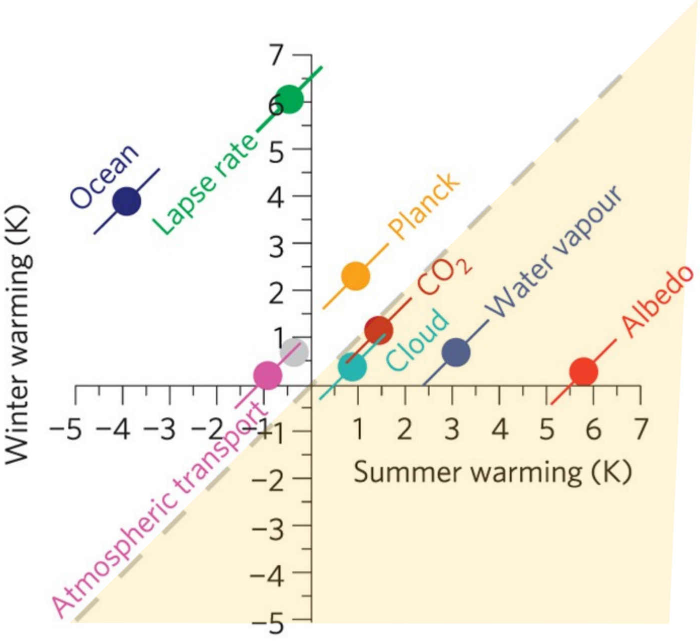
In the Arctic however the Planck feedback is less negative than in lower latitudes. This is because there are less blackbody emissions per unit warming at lower temperatures ($LWR = \varepsilon * \sigma T_e^4$)

However, as feedbacks are often defined in comparison to a global mean rather than local temperature change, the Planck feedback appears strongly negative in the Arctic because the local temperature change exceeds the local mean.

Goosse, H., Kay, J.E., Armour, K.C. et al. Quantifying climate feedbacks in polar regions. Nat Commun 9, 1919 (2018). https://doi.org/10.1038/s41467-018-04173-0

Arctic Amplification

Warming contributions of individual feedback mechanisms. Winter vs Summer warming



Summer warming

Cloud and water vapour

Depending on the cloud properties (ie height, type and thickness), clouds can either warm or cool the surface.

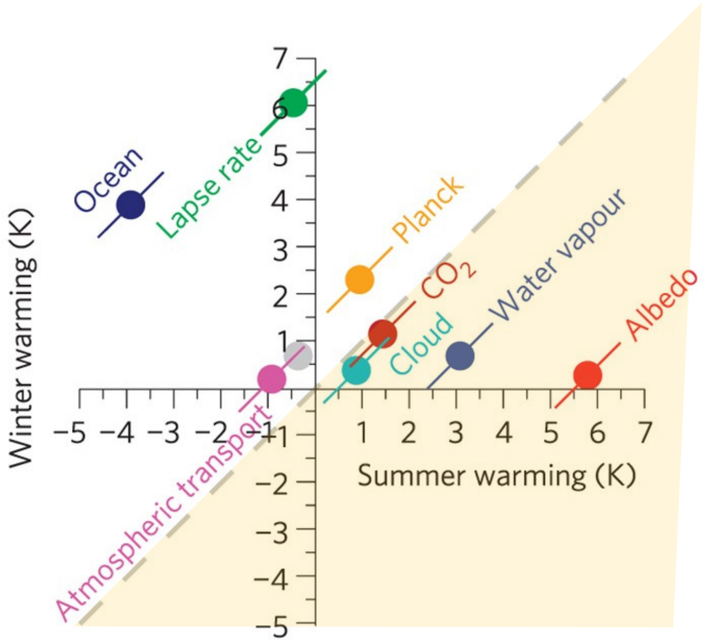
In summer, cloud feedbacks tend to have a **warming effect, (but they also cool for a few weeks)**:

- Low level clouds absorb longwave radiation, typical in the arctic summer
- As the sea ice melts, the increase in open water leads to more moisture in the atmosphere from increased ocean evaporation.
- Warmer temperatures lead to more water remaining in vapour phase and therefore more clouds. This leads to a positive feedback mechanism.

Water vapour itself is very effective at absorbing and emitting infrared radiation as well. As such, with increased moisture in the atmosphere due to warming, the greenhouse effect of water vapour increases.

Arctic Amplification

Warming contributions of individual feedback mechanisms. Winter vs Summer warming



Summer warming

Albedo

The **ice-albedo feedback** is one of the most significant contributors to Arctic amplification, especially during the summer months.

→ This feedback arises from the difference in reflectivity (albedo) between ice-covered and ice-free surfaces.

In summer, there is extensive sea ice and snow melt across the Arctic. **Ice and snow have a high albedo**, reflecting most of the incoming solar radiation back into space.

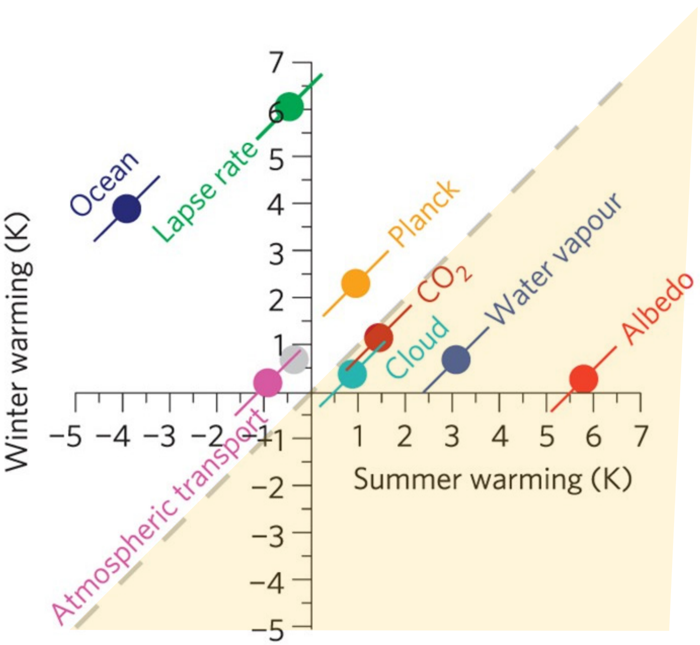
Open water however or ice-free land, has a much lower albedo meaning that more of the incoming solar radiation is absorbed and then emitted as longwave radiation, leading to further warming.

The additional absorbed heat accelerates the melting of more sea ice and snow, further lowering the Arctic's albedo and leading to more heat absorption.

Additionally … **ocean heat storage** can delay the onset of winter freezing and contribute to **permafrost thawing**, which releases additional greenhouse gases like methane and CO_2, further amplifying the warming.

Arctic Amplification

Warming contributions of individual feedback mechanisms. Winter vs Summer warming



Summer warming

CO_2 and anthropogenic emissions

As you know, CO_2 enhances the greenhouse effect by absorbing longwave radition and re-emitting it back towards the surface. This is not controlled by the seasons but more the cycle of local and long-range transport of pollutants.

LWR emission is amplified by the sea ice melt and loss during the summer leading to more ocean surface being exposed – ocean absorbs more heat.

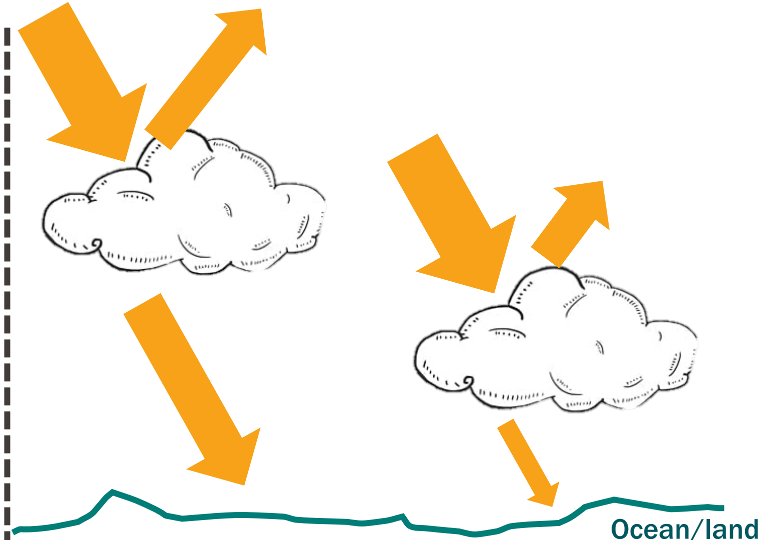
Low vs high level cloud feedback in the Arctic

First let us consider the incoming solar radiation (shortwave radiation) component

High albedo surfaces

High clouds transmit more SWR to the ground. All/most of what reaches the ground is then reflected back by the cold, icy surface

Low clouds transmit less SWR to the ground and reflect more upwards. The ground will then reflect back all/most of what SWR reaches it.



Low albedo surfaces

For warmer low albedo surfaces, incoming SWR is absorbed by the ground with little/none being reflected back.

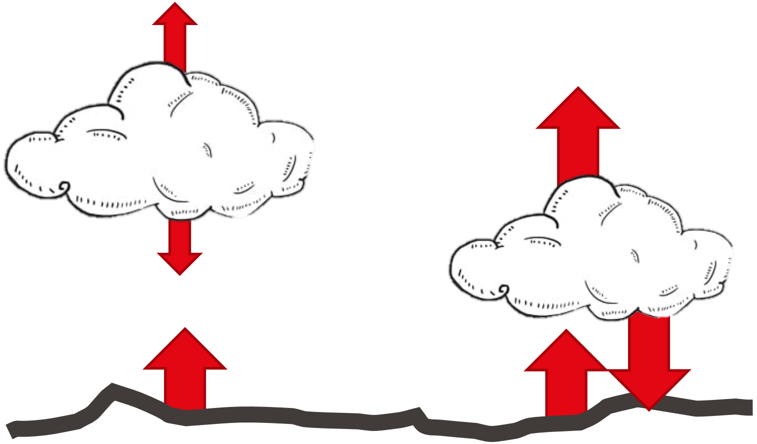
High level cloud
Cold, low liquid water content

Low level cloud
Warm, high liquid water content – usually more dense

Now we consider the black body radiation component (longwave radiation)

All bodies emit black body radiation and this is linked to their temperature with warmer bodies emitting much more. This radiation is not linked to the incoming solar radiation.

Colder high altitude clouds will emit less blackbody radiation than warmer low level clouds and the warmer surface.



High level cloud
Cold, low liquid water content

Low level cloud
Warm, high liquid water content

$$LWR = \varepsilon * \sigma T_e^4$$

Colder surfaces such as sea ice will emit less blackbody radiation than warmer surfaces such as the ocean. However this difference is much less than that of low vs high clouds.

Summary: Arctic Amplification

Winter	Summer
Ocean feedback **Ocean heat release**: Stored heat from the summer is released by the ocean, warming the atmosphere. Reduced sea-ice coverage allows more direct heat exchange between relatively warm ocean and the cold air.	**CO_2 feedback:** CO_2 absorbs and re-emits longwave radiation as everywhere else on the planet.
Atmospheric transport feedback: **Heat and moisture influx**: Warm moist air from lower latitudes are transported into the Arctic, enhancing cloud cover and absorbing and re-emitting longwave radiation.	**Cloud Feedback:** Increased moisture from open water leads to more cloud cover, which absorbs and re-emits longwave radiation near the surface through the greenhouse effect. This cloud cover often outweighs its cooling effect from reflecting sunlight, in particular over bright surfaces.
Lapse rate feedback: **Lapse rate remains positive**: because colder air, even if warmed by several tens of degrees, will not rise in a positive lapse rate situation and therefore heat accumulates at the surface	**Water Vapor Feedback:** As temperatures rise and sea ice melts, more evaporation occurs, increasing the amount of water vapor in the atmosphere. Water vapor is a potent greenhouse gas, reinforcing the warming in a positive feedback loop.
Planck feedback: **Enhanced warming**: A colder body radiates less than a warmer one. However the Arctic needs to equilibrate the same radiative forcing as the tropics, so it warms more in response to the forcing.	**Albedo Feedback:** The melting of sea ice and snow reduces the Arctic's albedo, allowing more solar radiation to be absorbed by the surface. This absorbed heat further accelerates ice melt and warms the Arctic more quickly, creating a powerful positive feedback.

EPFL MOSAiC

MOSAiC

Setting up the ice camp for the MOSAiC expedition. Polarstern - left; Akademik Federov - right. (picture credit: Jan Rohde)

Multidisciplinary drifting
Observatory for the
Study of
Arct**i**c
Climate

MOSAiC was the largest polar expedition in history setting sail from Tromsø, Norway in September 2019 on the German Icebreaker Polarstern.

The Polarstern, with its rotating complement of 442 researchers from over 20 countries worldwide, spent an entire year stuck in the seaice, drifting through the Arctic Ocean.

The aim was to gain fundamental insights that are key to better understand global climate change bringing a modern research icebreaker close to the north pole for a full year including for the first time in polar winter.

EPFL

Multidisciplinary drifting Observatory for the Study of Arctic Climate

❄ Not on exam – just for interest ☺ ❄

389 days

The expedition's duration was 389 days.

7 icebreakers/ships

During the expedition, RV Polarstern was resupplied by 6 additional icebreakers and research ships from Russia and Germany.

60 polar bears

More than 60 polar bears were sighted near the Polarstern.

-42 °C

-42.3 °C, the lowest temperature encountered on the expedition, was reached on 10 March 2020.

156 km

During her first drift Polarstern reaches 88°36′ North, just 156 kilometres from the North Pole.

1500 km

Polarstern was up to 1500 km from the nearest human settlement.

36278 m

36,278 m: the altitude of the highest measurements taken in the atmosphere.

4297 m

4,297 m: the deepest point in the ocean at which the expedition took measurements.

https://mosaic-expedition.org/

EERL Polar Research

ALPACA

Surface-based inversions and pollution dispersion

Greenfjord

Effect of evolving fjord systems on clouds

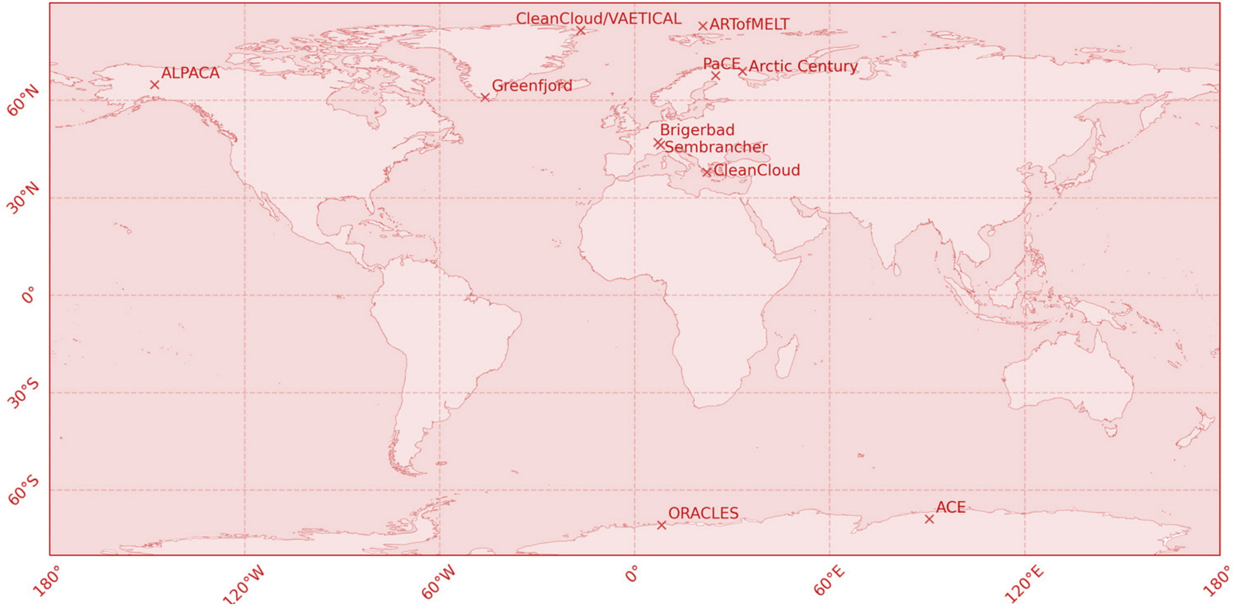
VAERTICAL

Vertical properties of aerosols in the Arctic lower atmosphere and their impact on cloud radiative effects

ARTofMELT

Transport of aerosols from mid-latitudes by WAMIs

EERL Field Campaigns



PaCE

Pallas Cloud Experiment

ORACLES

ORigin of Antarctic CLoud particles and their Effect on Surface radiative budget

https://www.epfl.ch/labs/eerl/

Take home message

- Temperatures in the Arctic are increasing 3 to 4 times faster than the rest of the world. This phenomenon is called Arctic amplification.
- The Arctic amplification is more pronounced in winter and is a consequence of several feedback mechanisms, including the lapse rate and Planck feedback.
- Warming of the Arctic and ice melt has strong consequences for weather and climate in the rest of the world.