UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH

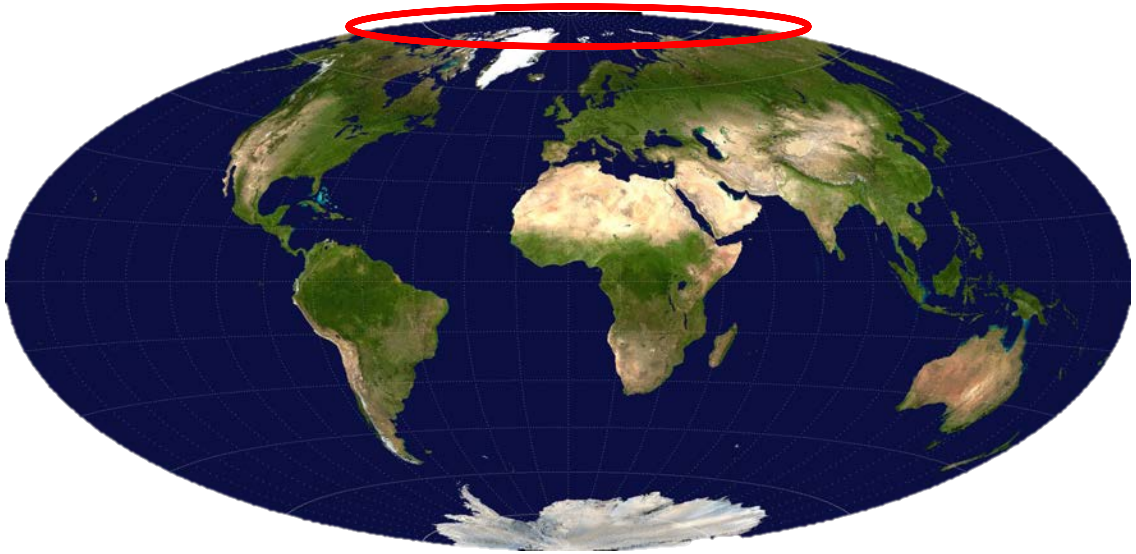
# Stressors of Arctic Ocean ecosystems:
## Improved understanding of primary production and ocean acidification

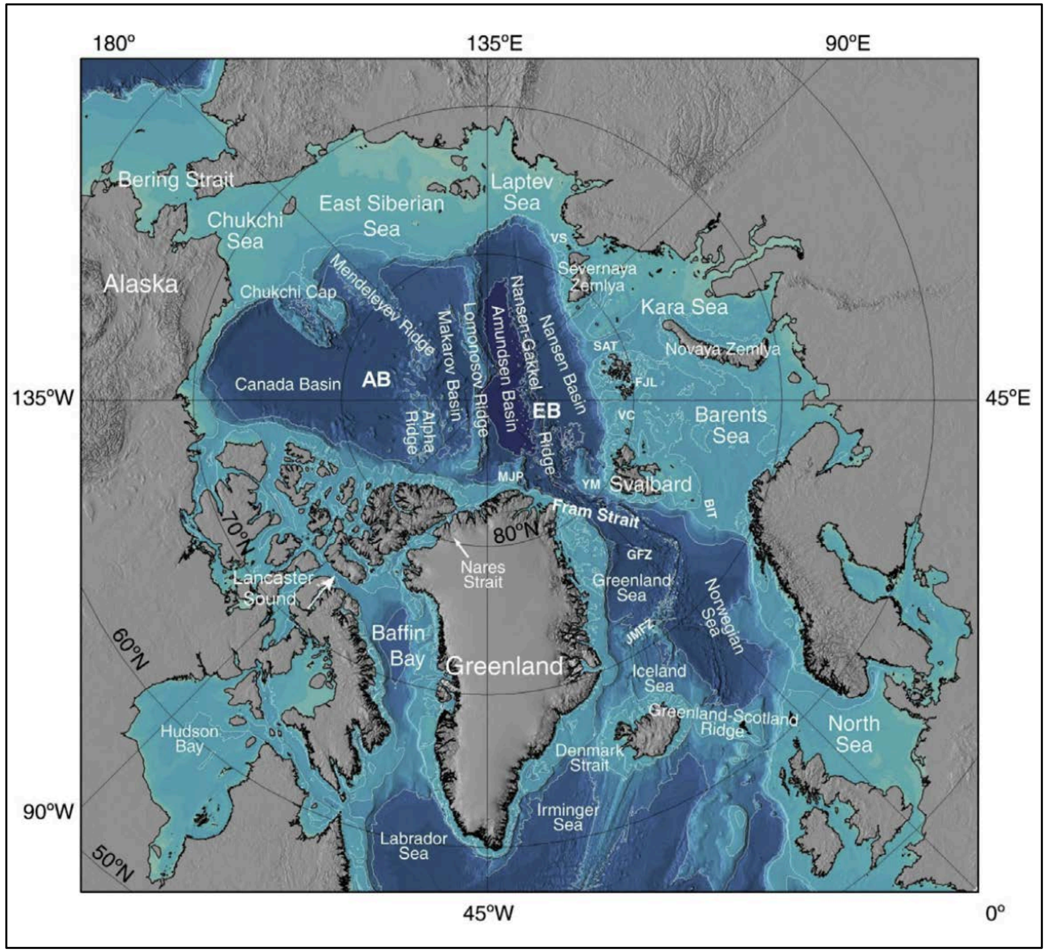
ARCUS Arctic Research Seminar Series
16th August 2021

**Jens Terhaar**
Physics Institute - Climate and Environmental Physics
Oeschger Centre for Climate Change Research
University of Bern

jens.terhaar@climate.unibe.ch

# The Arctic Ocean – Top of the world



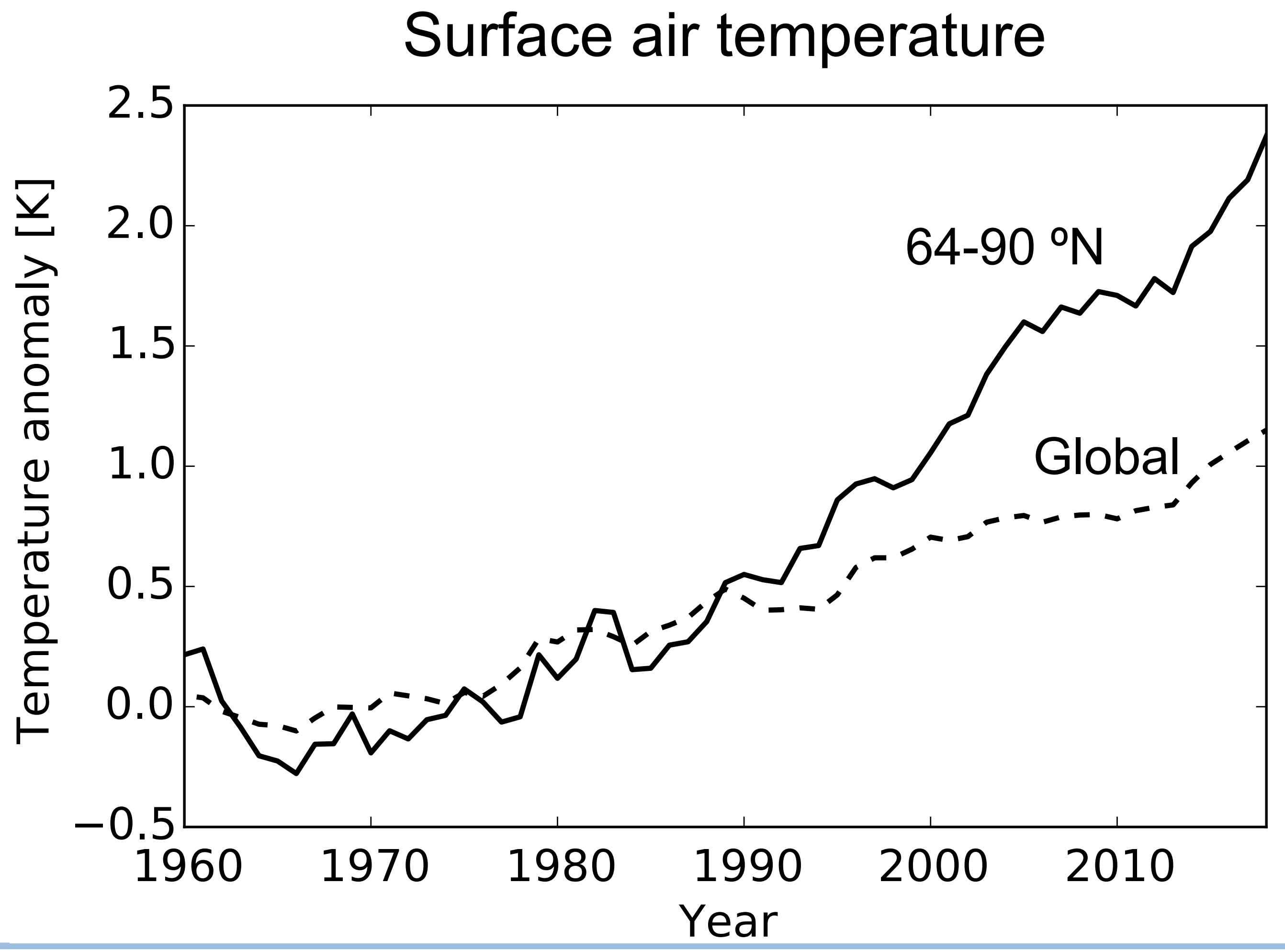



- Almost entirely encircled by land
- Only narrow passages with adjacent oceans
- 50% of its area is made up by shelf seas

Rudels, 2015

# Climate change is amplified in the Arctic

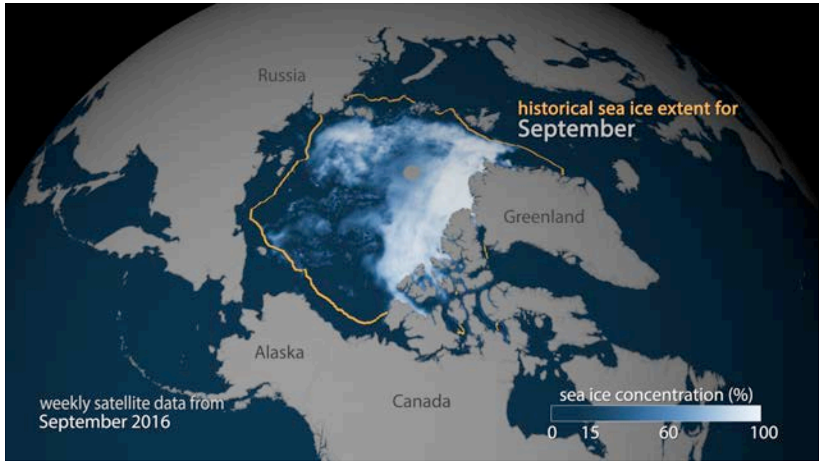
UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH

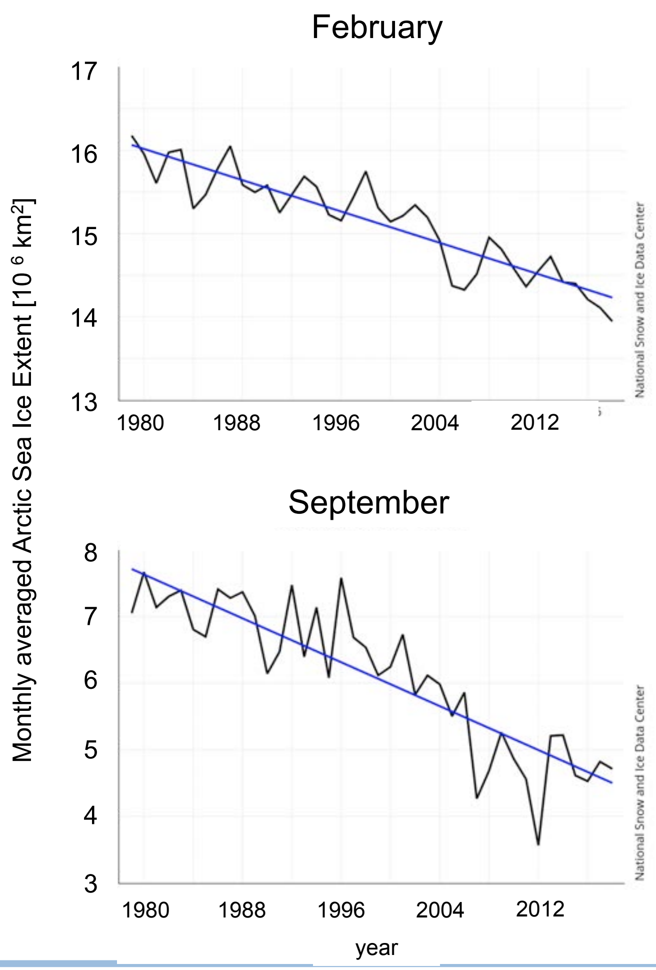



Data from https://data.giss.nasa.gov/gistemp/

# Rapid ongoing decline in Arctic Sea Ice

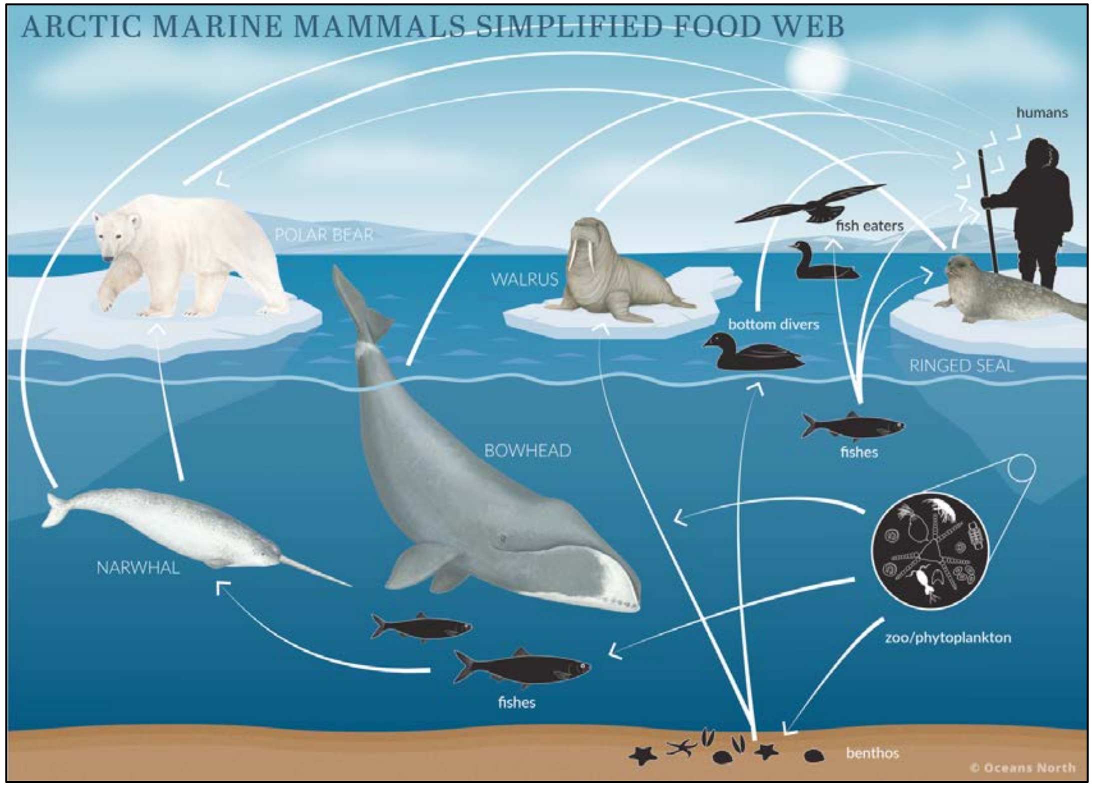
UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH

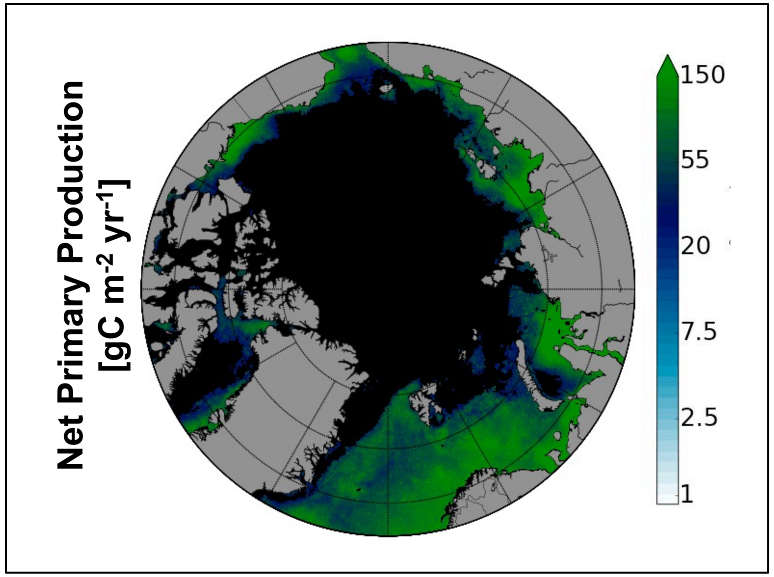



# Changes in sea ice cover and temperature may well affect the Arctic ecosystem, e.g. by increasing net primary production

UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH

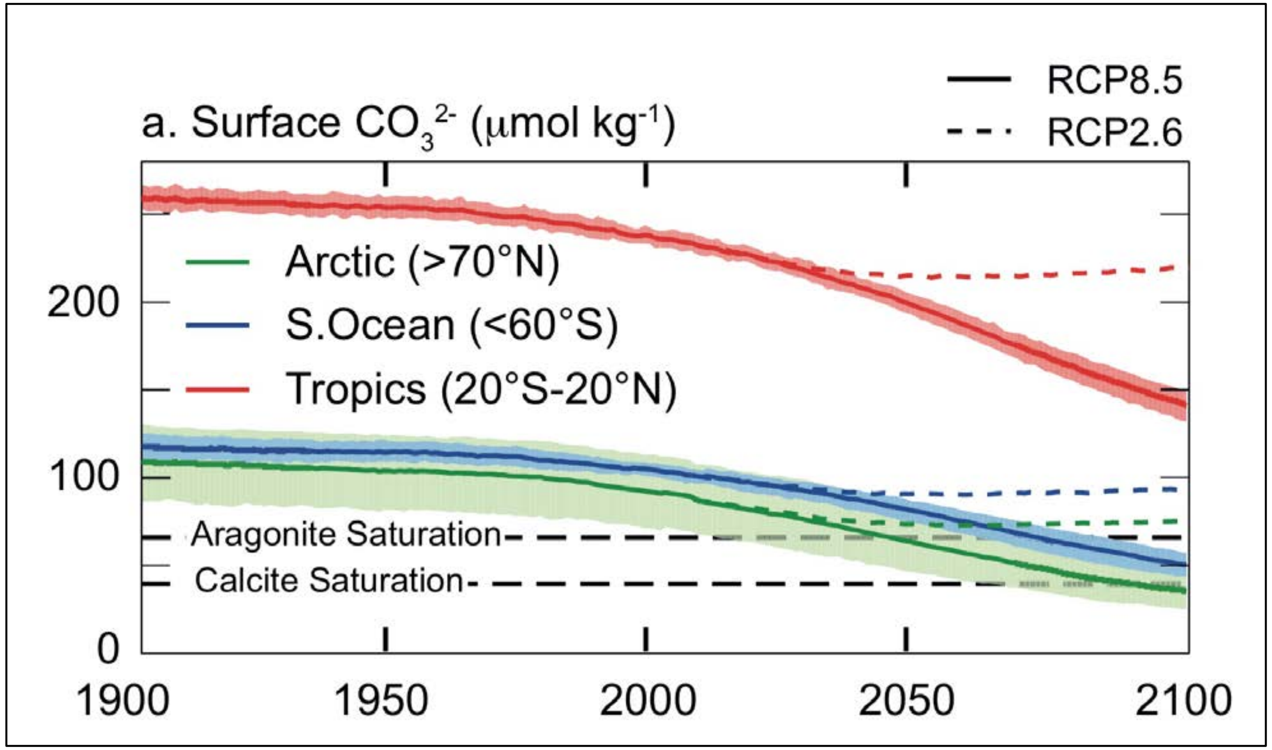



Oceans North (https://oceansnorth.org/)




- Arctic Ocean NPP is limited by
  - Light (Sea ice and Arctic winter)
  - Nitrogen
- Arctic Ocean NPP has increased by 57% from 1998 to 2018 (Lewis et al., 2020)

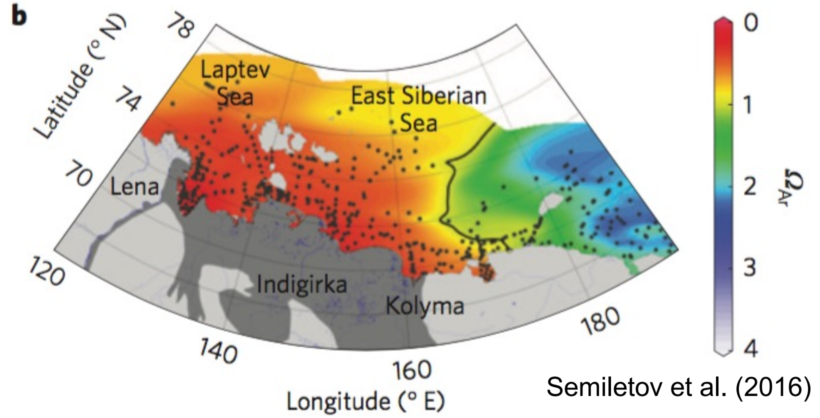
# Arctic Ocean is particularly vulnerable to ocean acidification



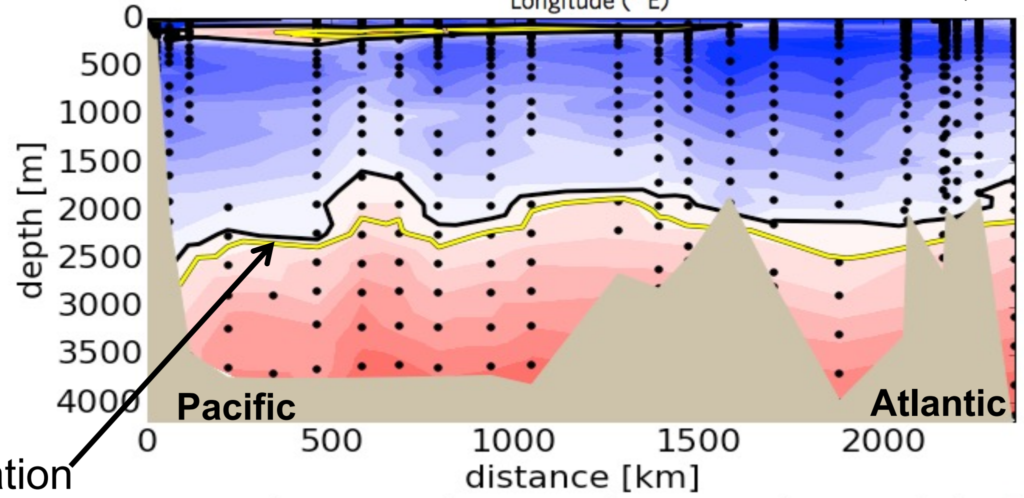

Ciais et al., 2013

$$CO_3^{2-} \approx A_T - C_T$$

## Observations in the Laptev Sea




Semiletov et al. (2016)

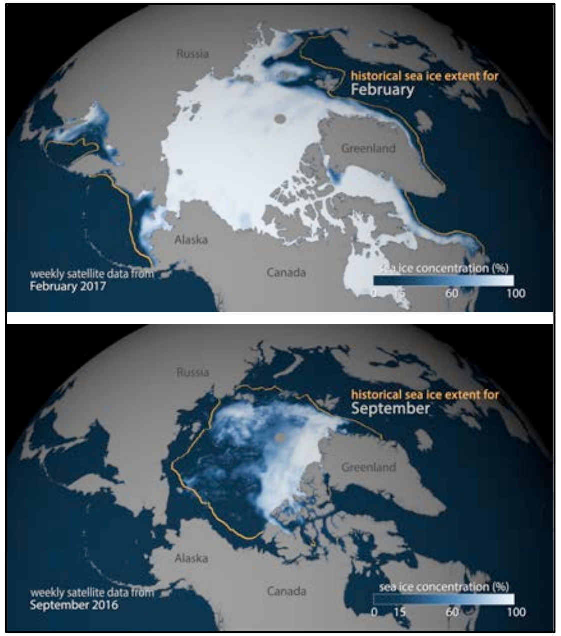



Deep aragonite saturation horizon (ASH)

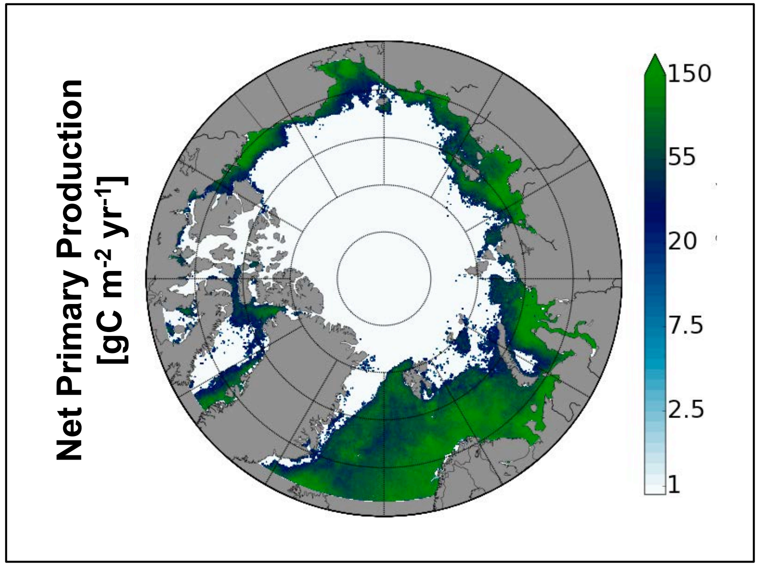
Terhaar et al., 2020

# Climate models prone to large uncertainties in the Arctic Ocean






No summer sea ice left by 2021-2043
(Wang et al., 2012)




NPP change during 21st century: -25% to +60%
(Vancoppenolle et al., 2013)


Surface $\Omega_A$ in 2075: 0.5-0.8
(Steiner et al., 2014)

# Research questions

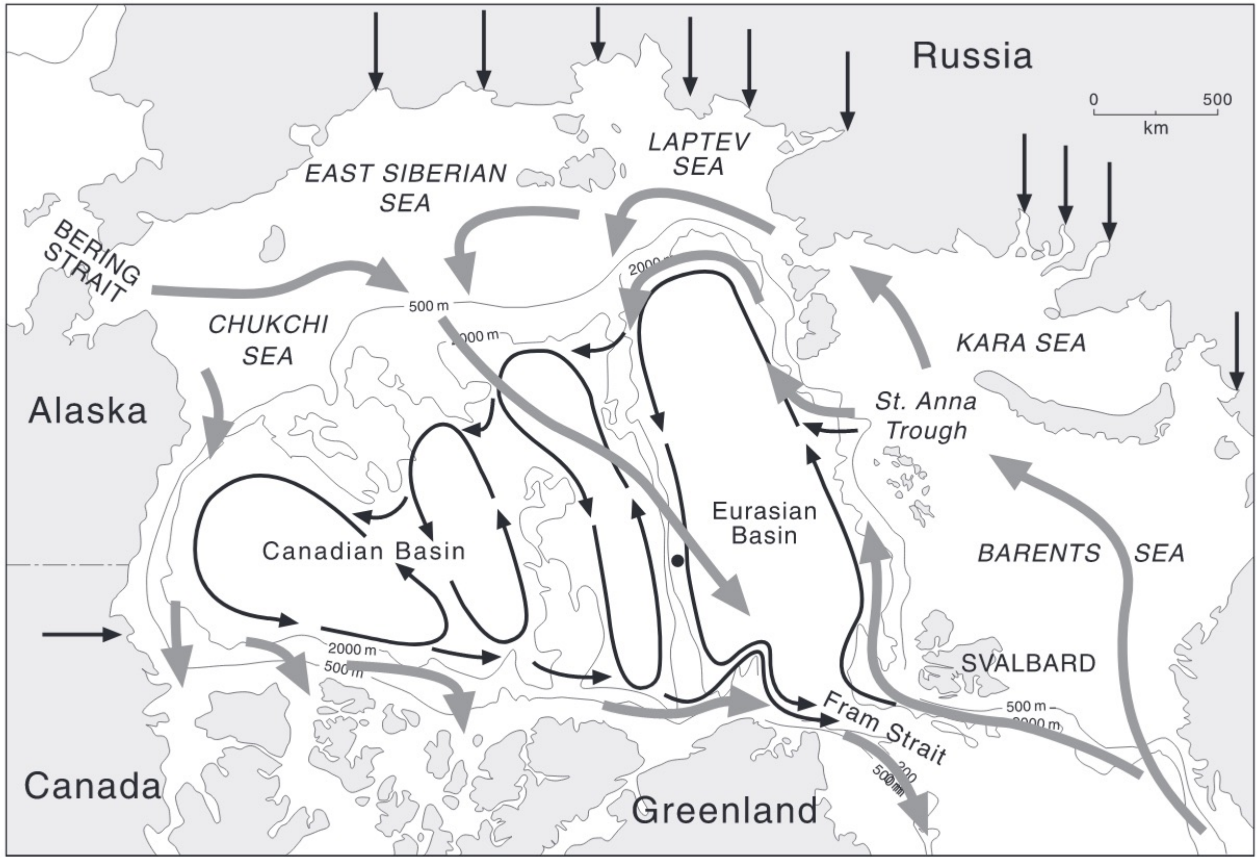
UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH

1) Can we improve/constrain ocean acidification projections in the Arctic Ocean?

2) How important is riverine nutrient delivery for the Arctic Ocean net primary production?

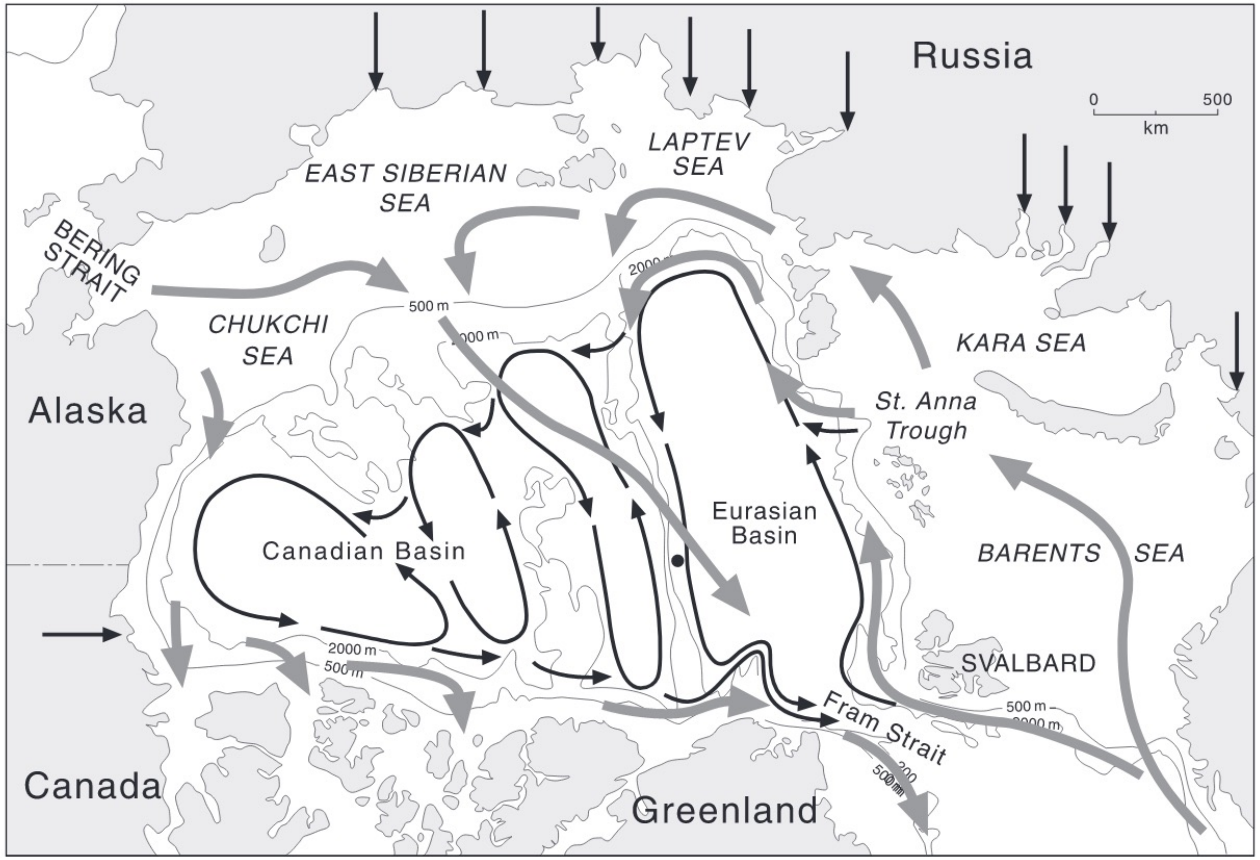
# Global climate models have difficulties to resolve the Arctic bathymetry and thus to well simulate the Arctic Ocean circulation





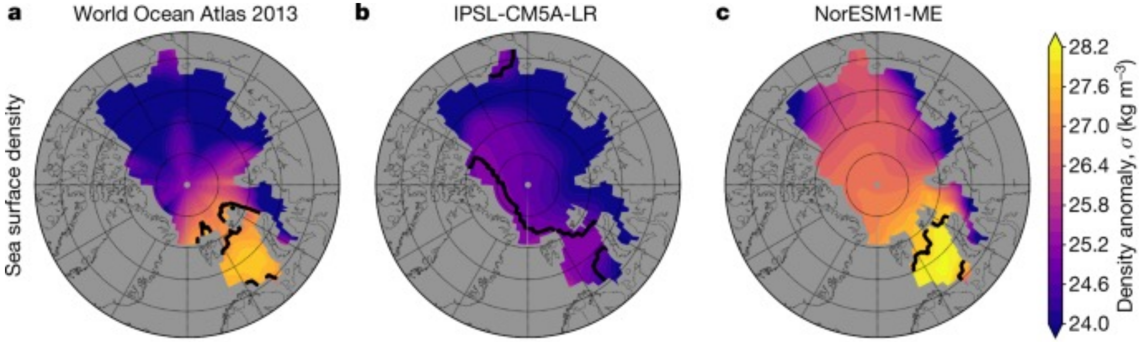

Jones, 2001

# Global climate models have difficulties to resolve the Arctic bathymetry and thus to well simulate the Arctic Ocean circulation




Jones, 2001

Annual sea surface density



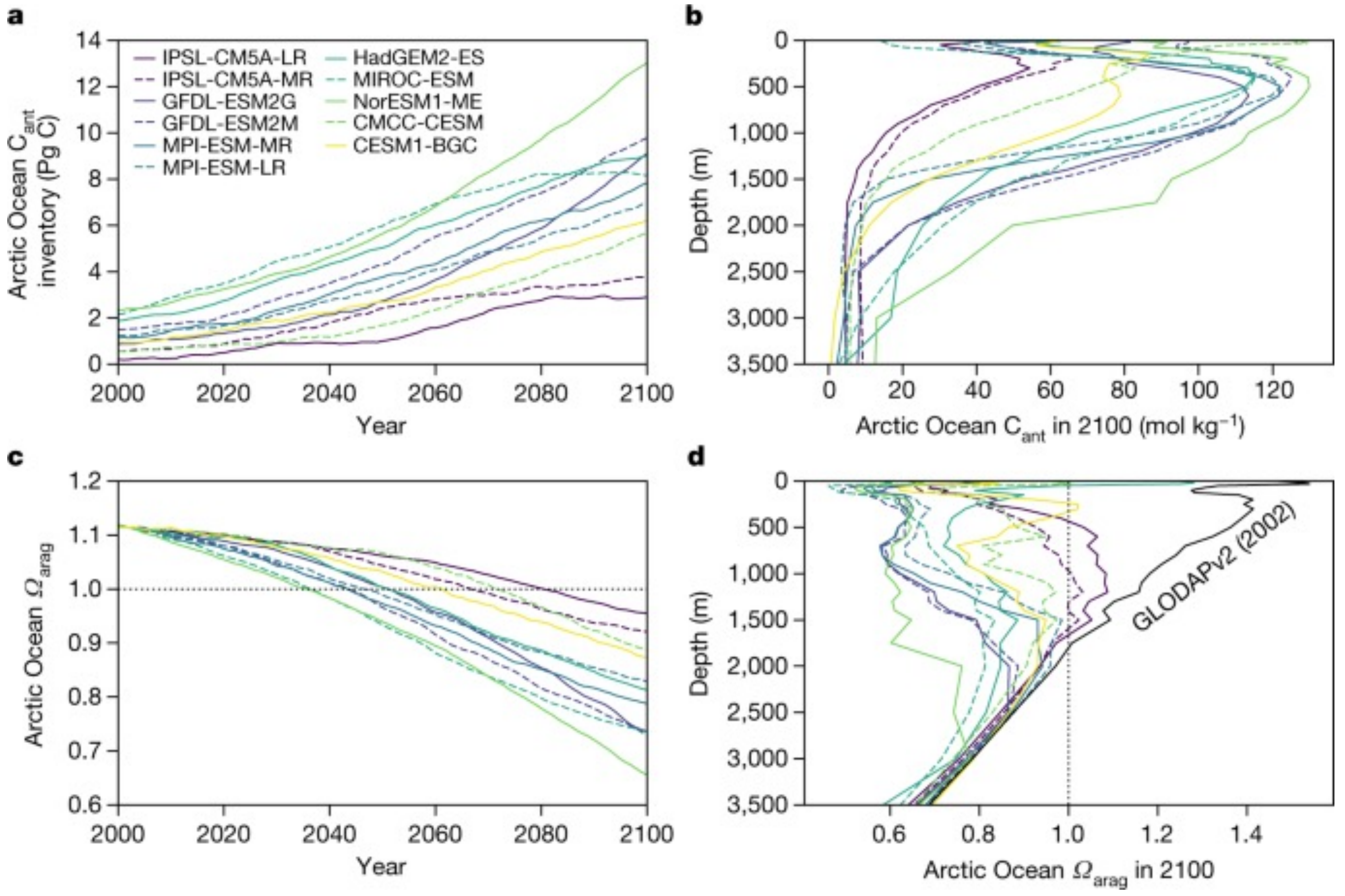

Terhaar et al. (2020)

- Simulated core depth of Atlantic Water: 250 to 1000 m (Shu et al., 2019)
- Simulated core temperature of Atlantic Water: -1.5 to 3℃ (Shu et al., 2019)
- Lateral inflow of anthropogenic carbon from 1960-2012: -0.3 Pg C to +1.1 Pg C (Terhaar et al., 2019)

# Earth-System Model ensembles exhibit a large range of projected $C_{ant}$ inventories and associated saturation states in the Arctic Ocean

UNIVERSITÄT BERN

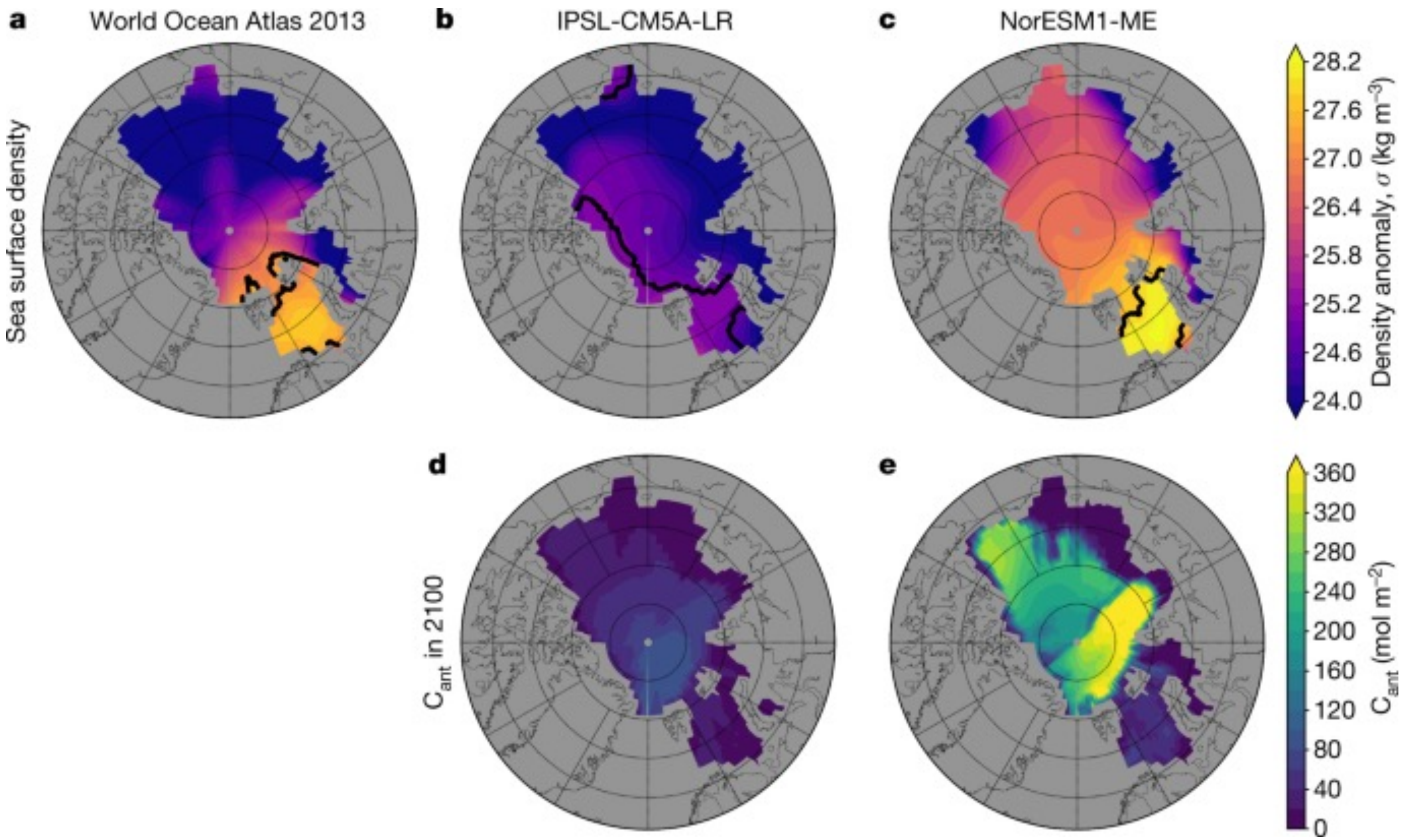
OESCHGER CENTRE CLIMATE CHANGE RESEARCH




Terhaar et al., 2020

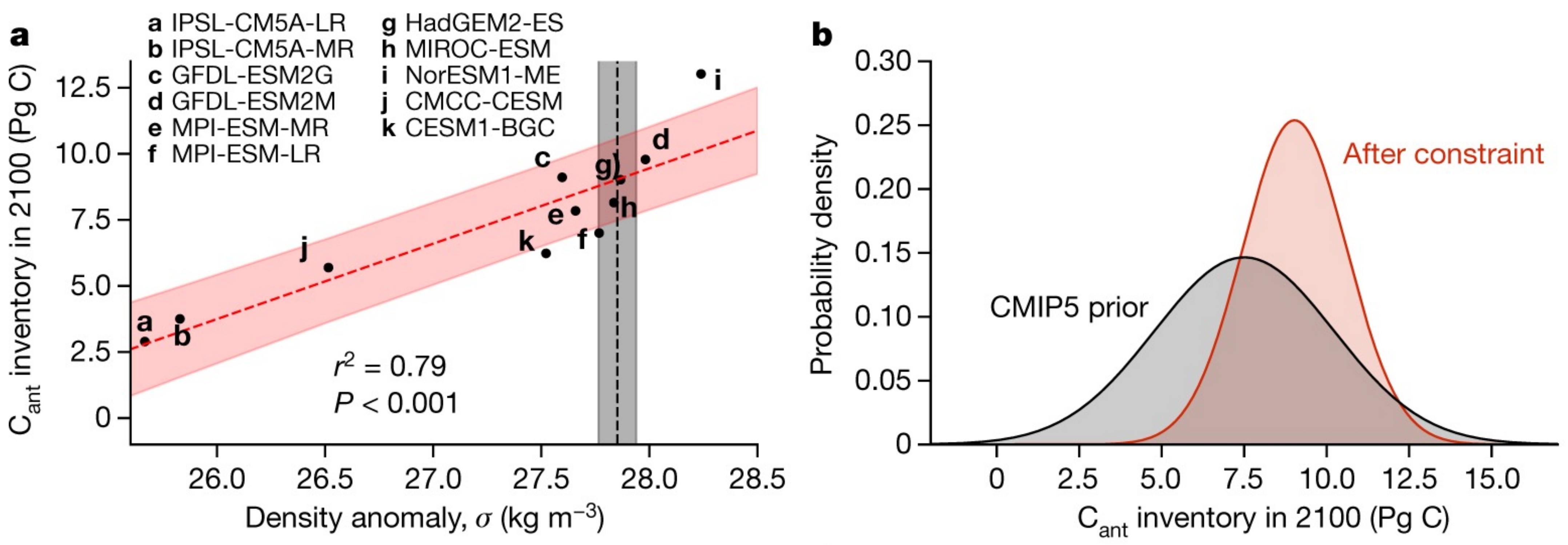
# The maximum sea surface density determines the deep-water formation in the Arctic Ocean and hence the $C_{ant}$ accumulation over the 21st century

b UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH




Terhaar et al., 2020

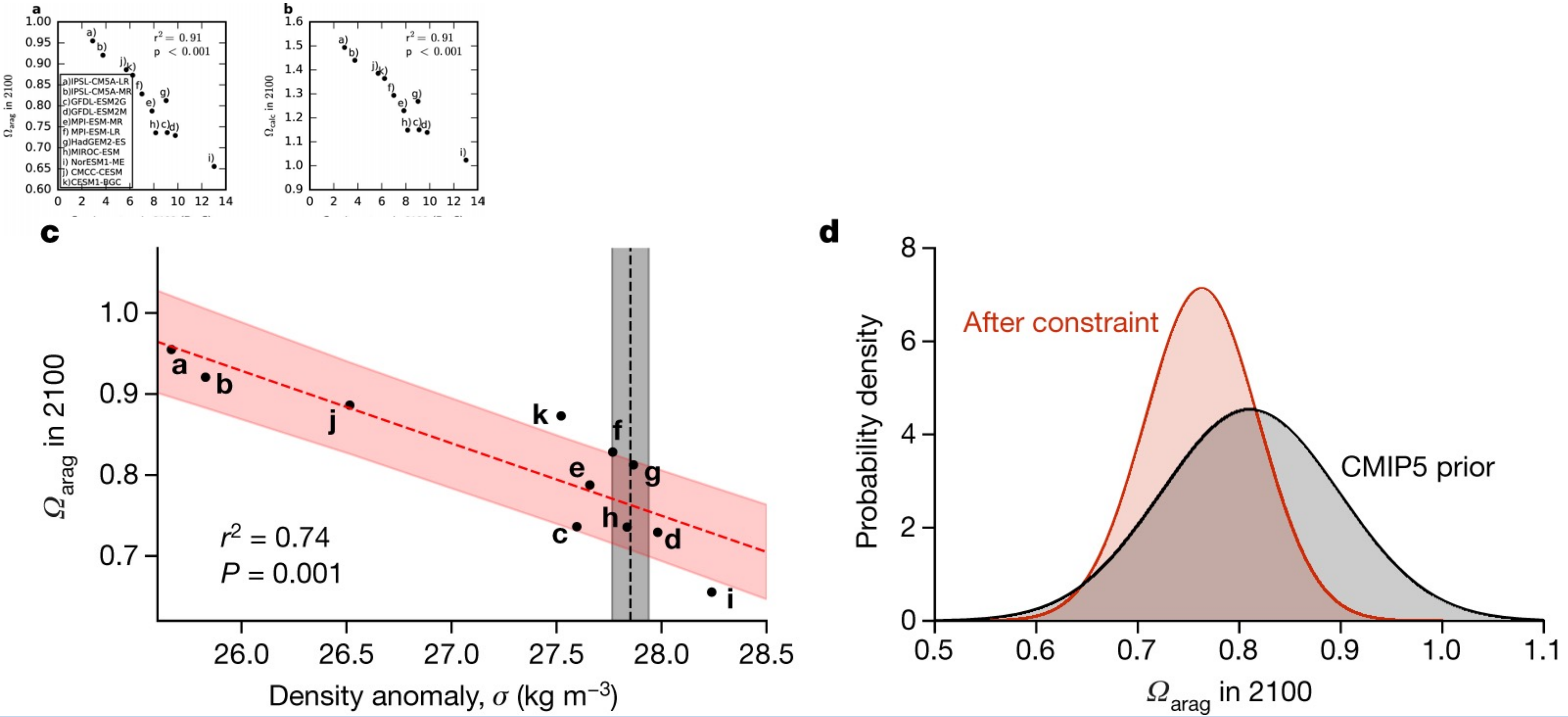
# Across the CMIP5 ensembles a strong relationship exists between sea surface densities in the Barents Sea and $C_{ant}$ accumulation




Terhaar et al., 2020

# The $C_{ant}$ inventory in 2100 is strongly anti-correlated to the basin-wide $CaCO_3$ saturation states in 2100, allowing to constrain these as well

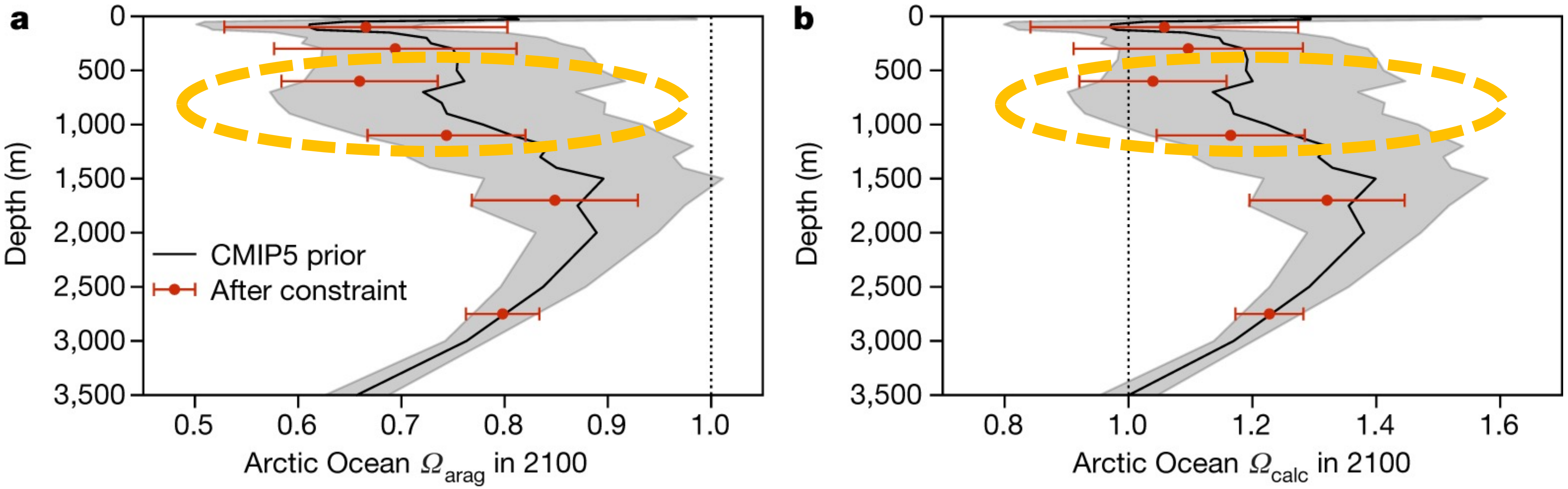
UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH




Terhaar et al., 2020

# The reduction in uncertainties of the projected saturation states is largest in mesopelagic waters

UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH

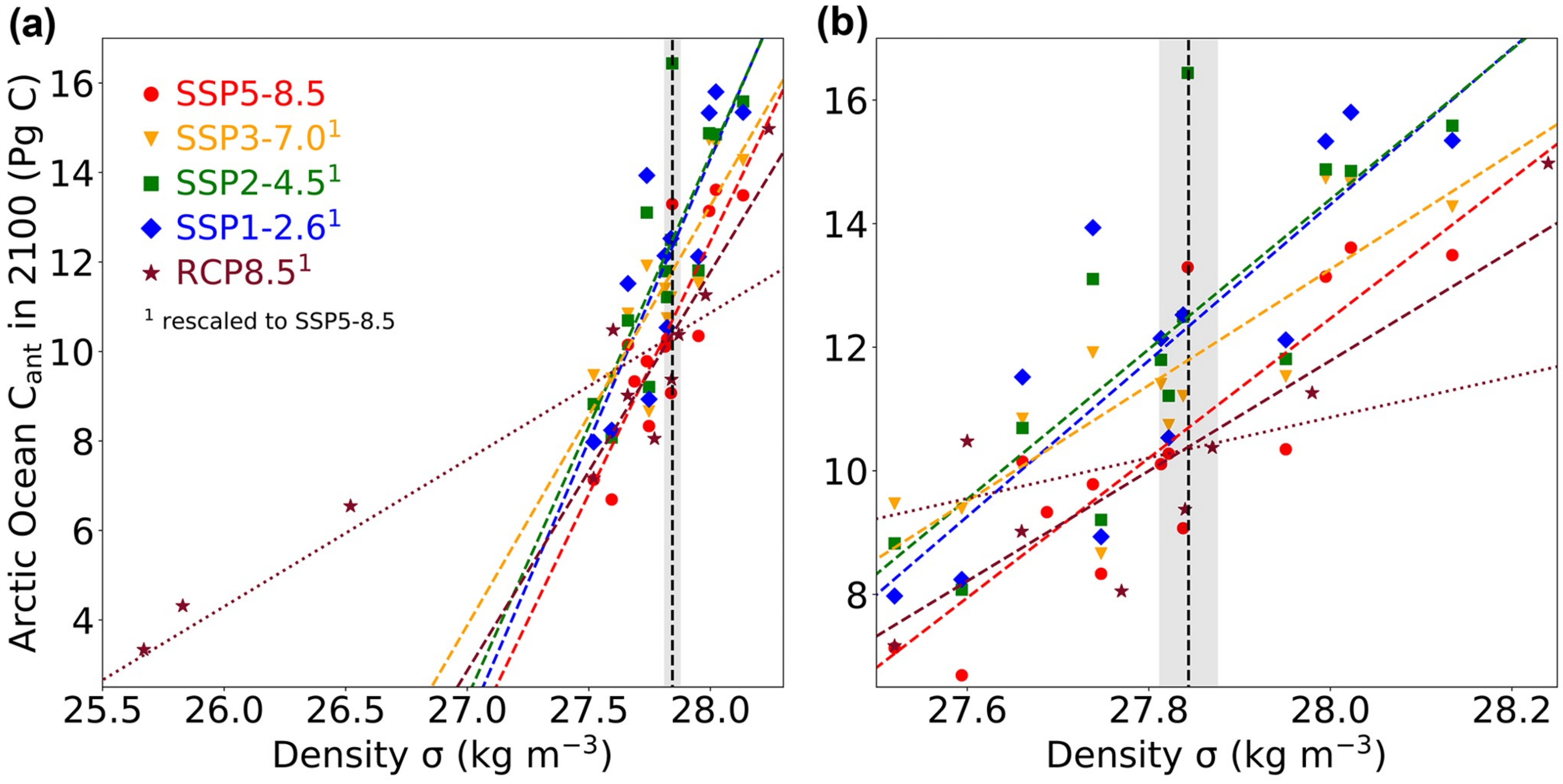



Terhaar et al., 2020

# CMIP6 results show that the emergent relationship between $C_{ant}$ and sea surface density is non-linear

UNIVERSITÄT BERN

OESCHGER CENTRE CLIMATE CHANGE RESEARCH



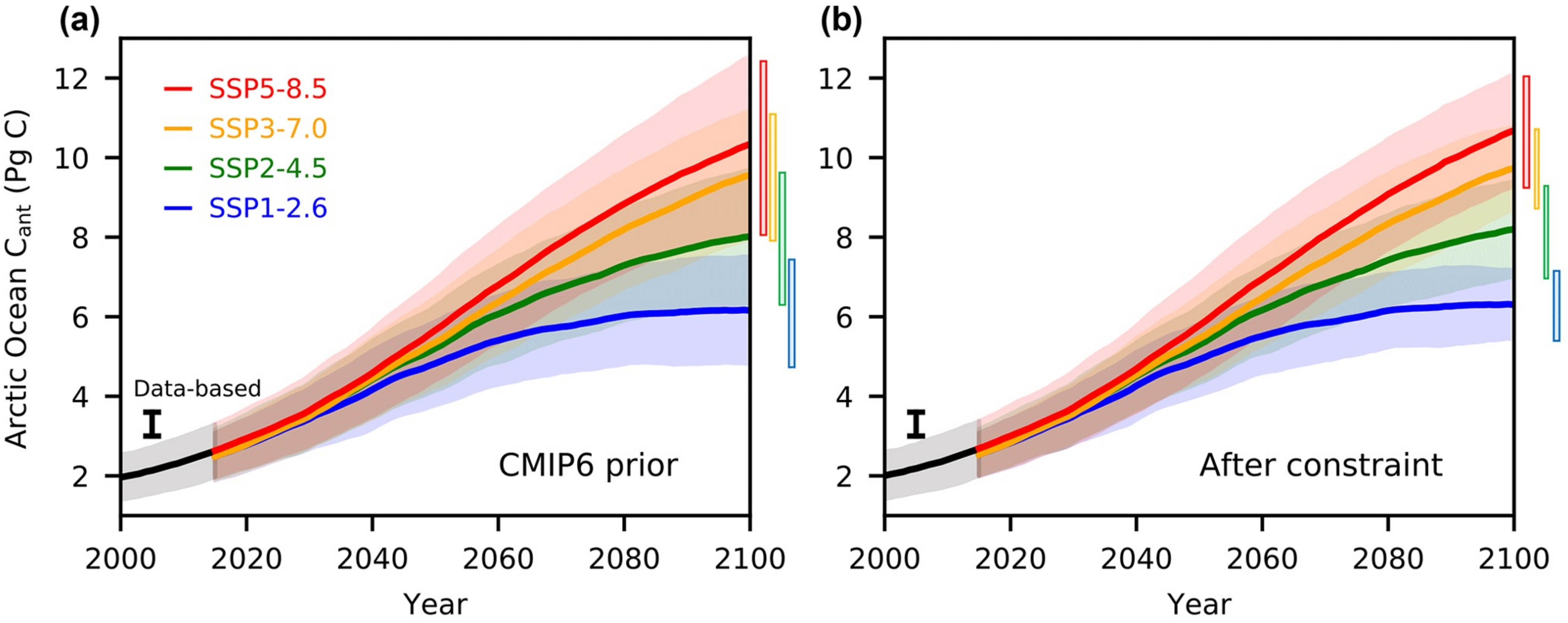

*All inventories are rescaled to the SSP5-8.5 atmoshperic $C_{ant}$ concentrations

Terhaar et al., 2021

# The relationship allows to reduce the projected $C_{ant}$ inventory also across the CMIP6 model ensemble

UNIVERSITÄT BERN

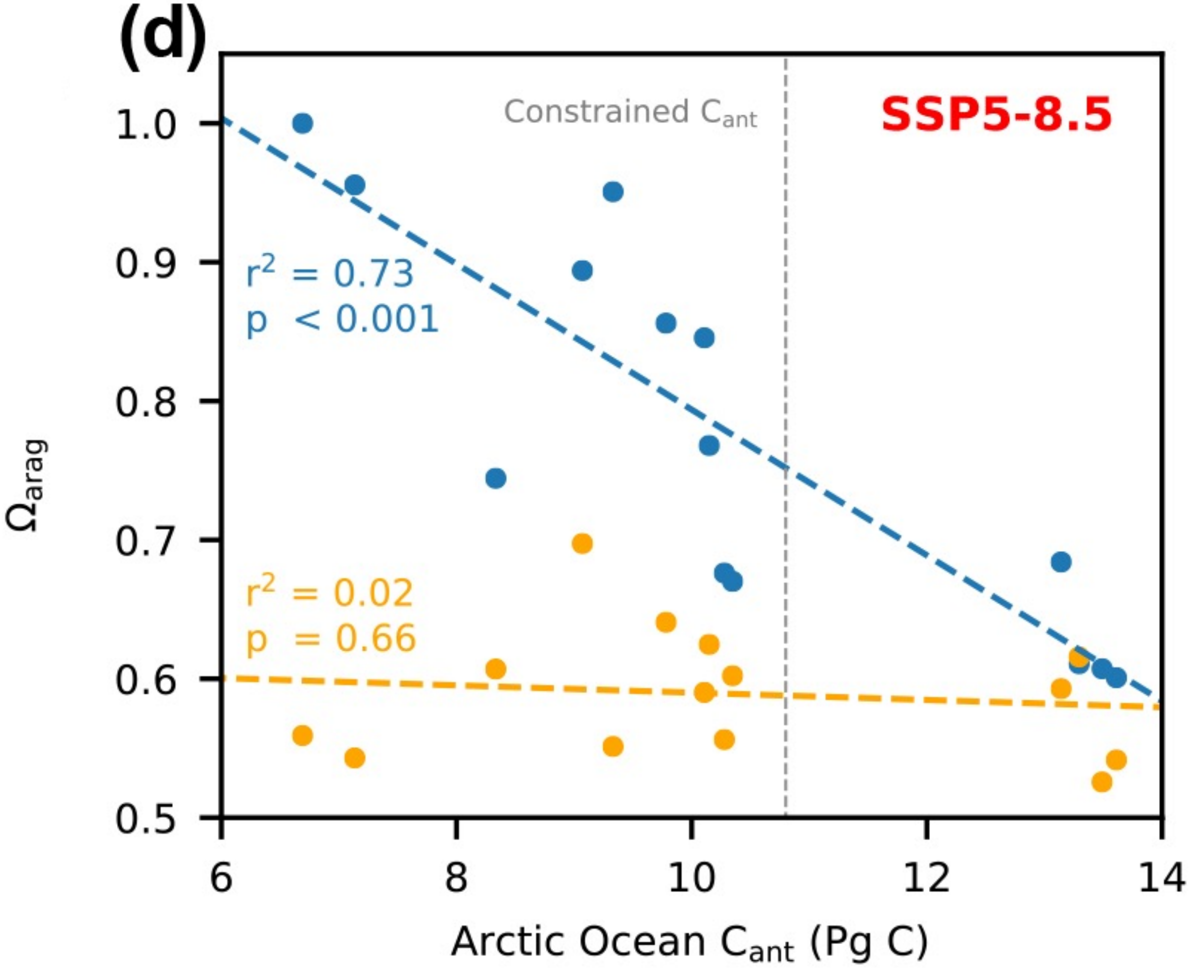
OESCHGER CENTRE CLIMATE CHANGE RESEARCH




Terhaar et al., 2021

# However, in CMIP6 no relationship exists between $C_{ant}$ accumulation and Arctic Ocean saturation states

UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH



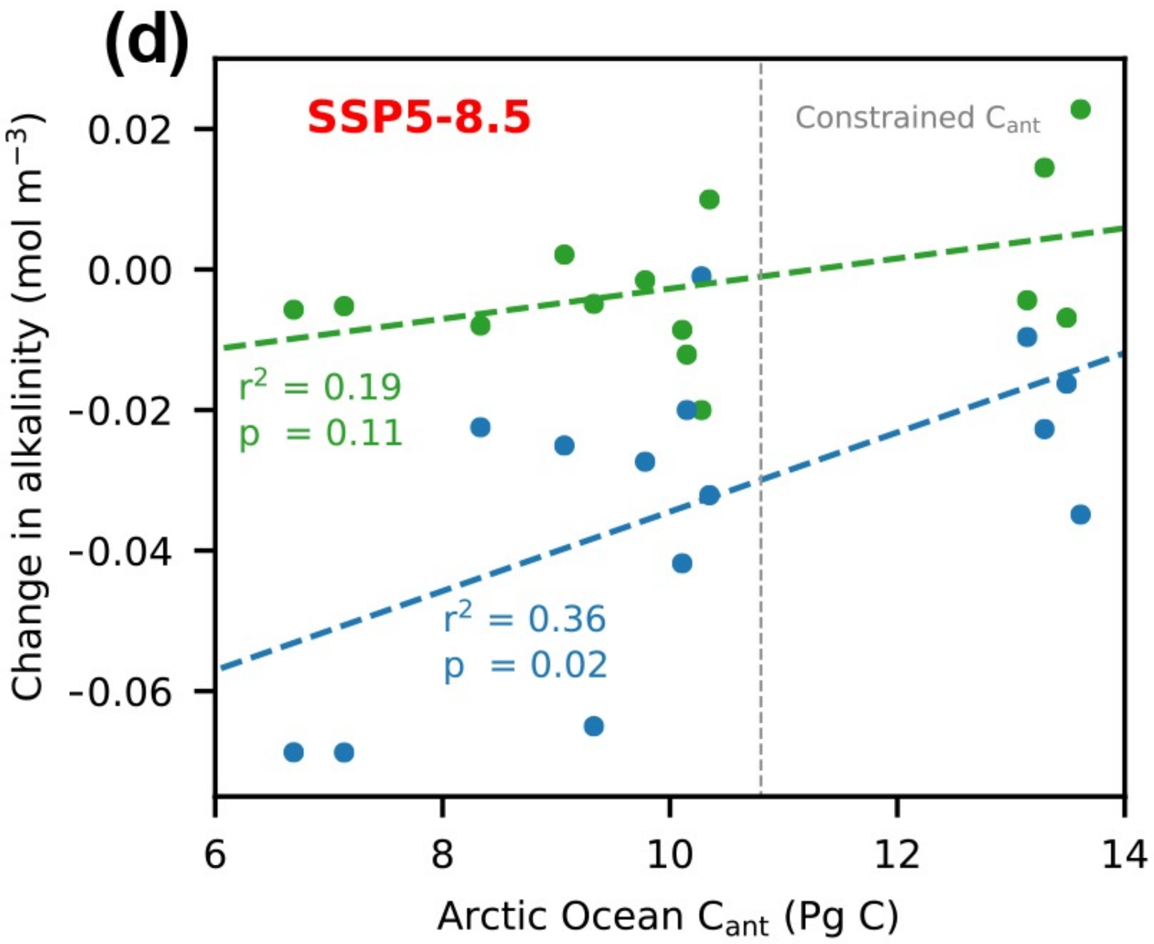

All drivers
Without $A_T$

Terhaar et al., 2021

# Models with more freshening take up less anthropogenic carbon but simulate a stronger reduction in alkalinity

UNIVERSITÄT BERN

OESCHGER CENTRE CLIMATE CHANGE RESEARCH



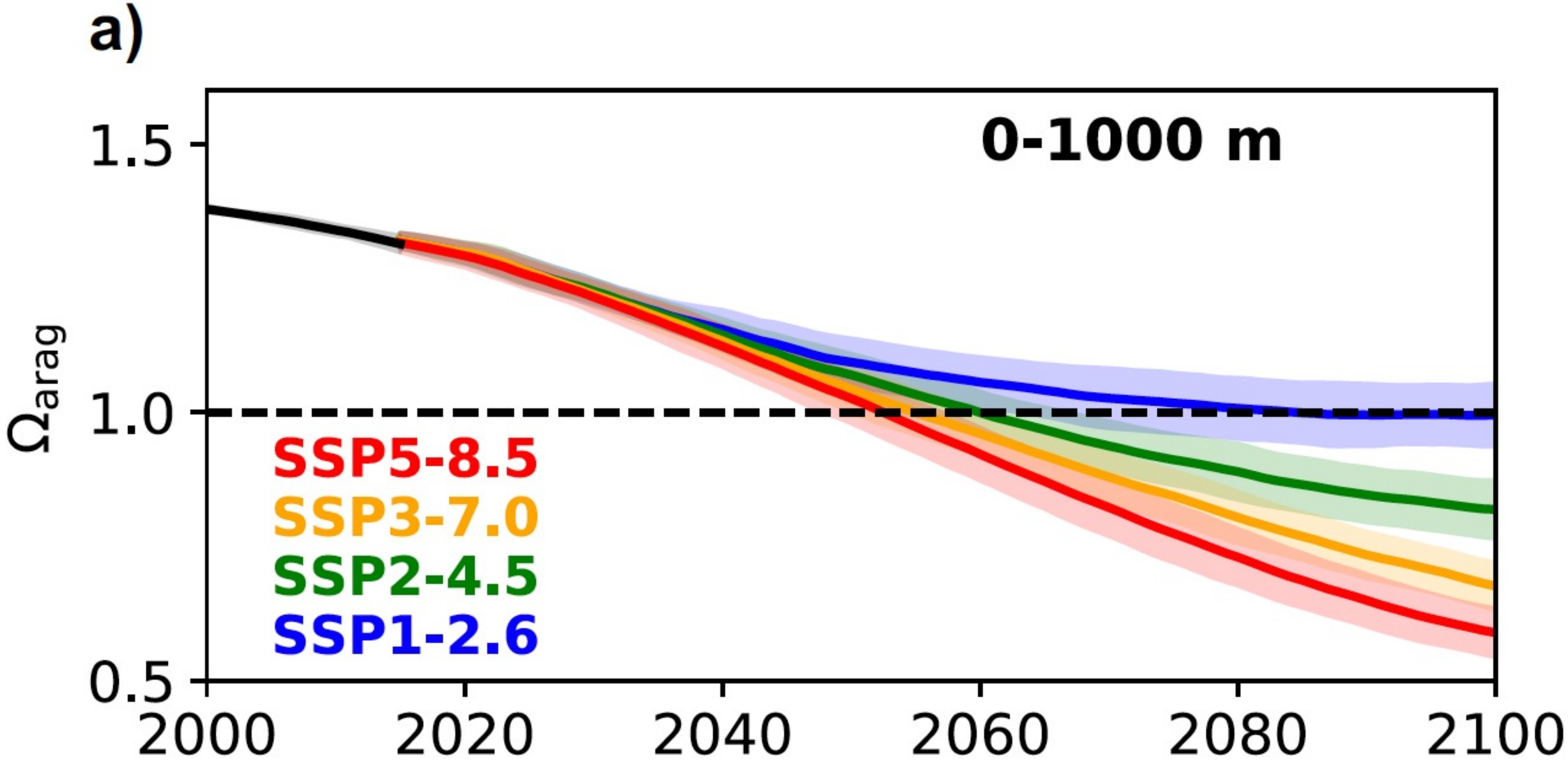

Freshening

Biogeochemistry

Terhaar et al., 2021

# The compensation (low $C_{ant}$ inventory, large decreases in $A_T$ and vice versa) reduces uncertainties in the projections of $CaCO_3$ saturation states in CMIP6 models

UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH




Terhaar et al., 2021

# Take home messages



1) Projections of carbon uptake and ocean acidification by Climate Models can be better constrained by the maximum sea surface density

2) The range of projections of Arctic Ocean acidification is reduced in CMIP6 due to more realistic surface ocean conditions and enhanced freshening

3) The Arctic Ocean will on average become undersaturated towards aragonite independend of the scenario

## Research questions

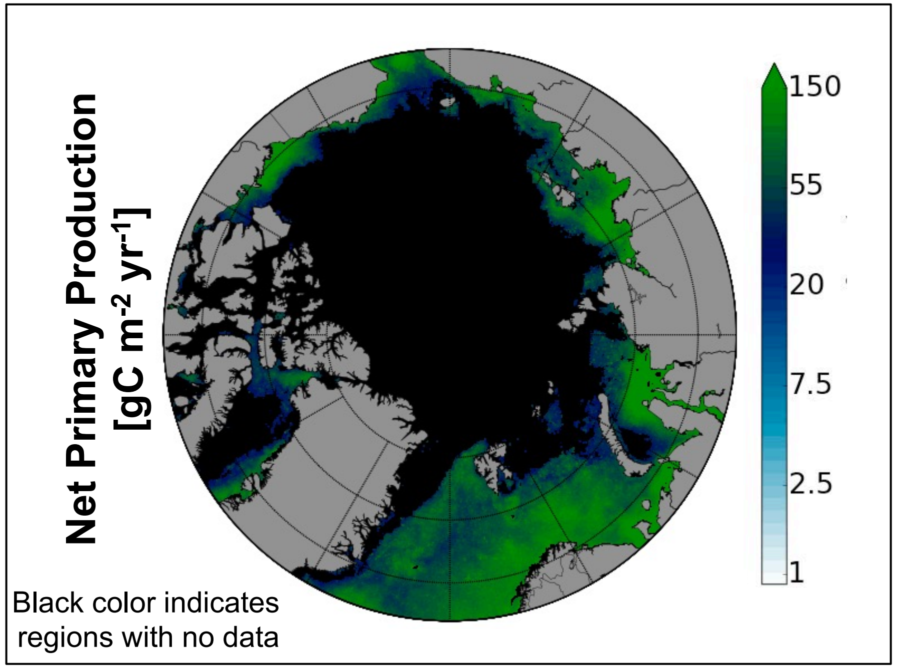


1) Can we improve/constrain ocean acidification projections in the Arctic Ocean?

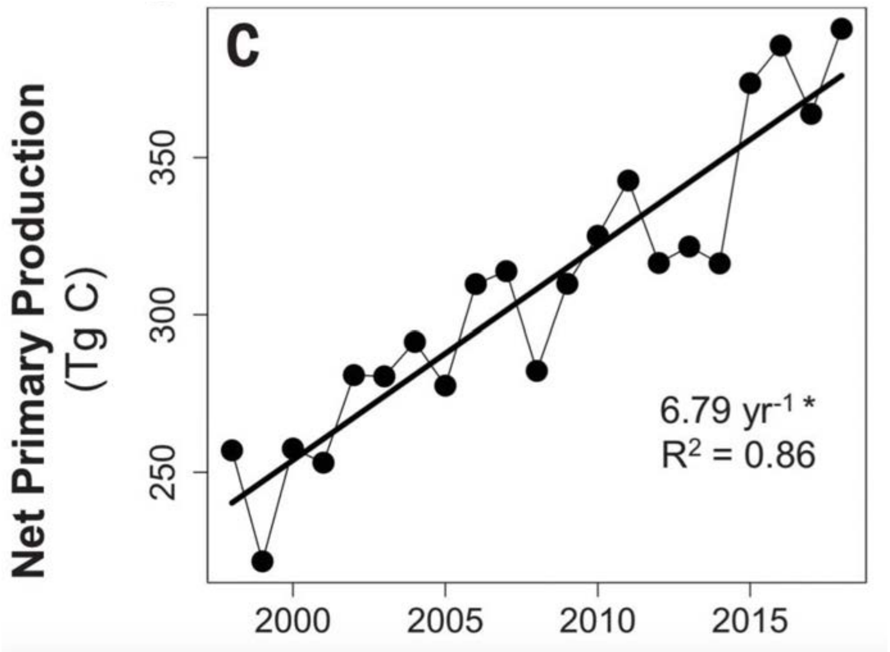
2) **How important is riverine nutrient delivery for the Arctic Ocean net primary production?**

# This Arctic Ocean NPP evolves rapidly with a changing climate

UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH




Annual data-based NPP derived from Arrigo & van Dijken, 2015

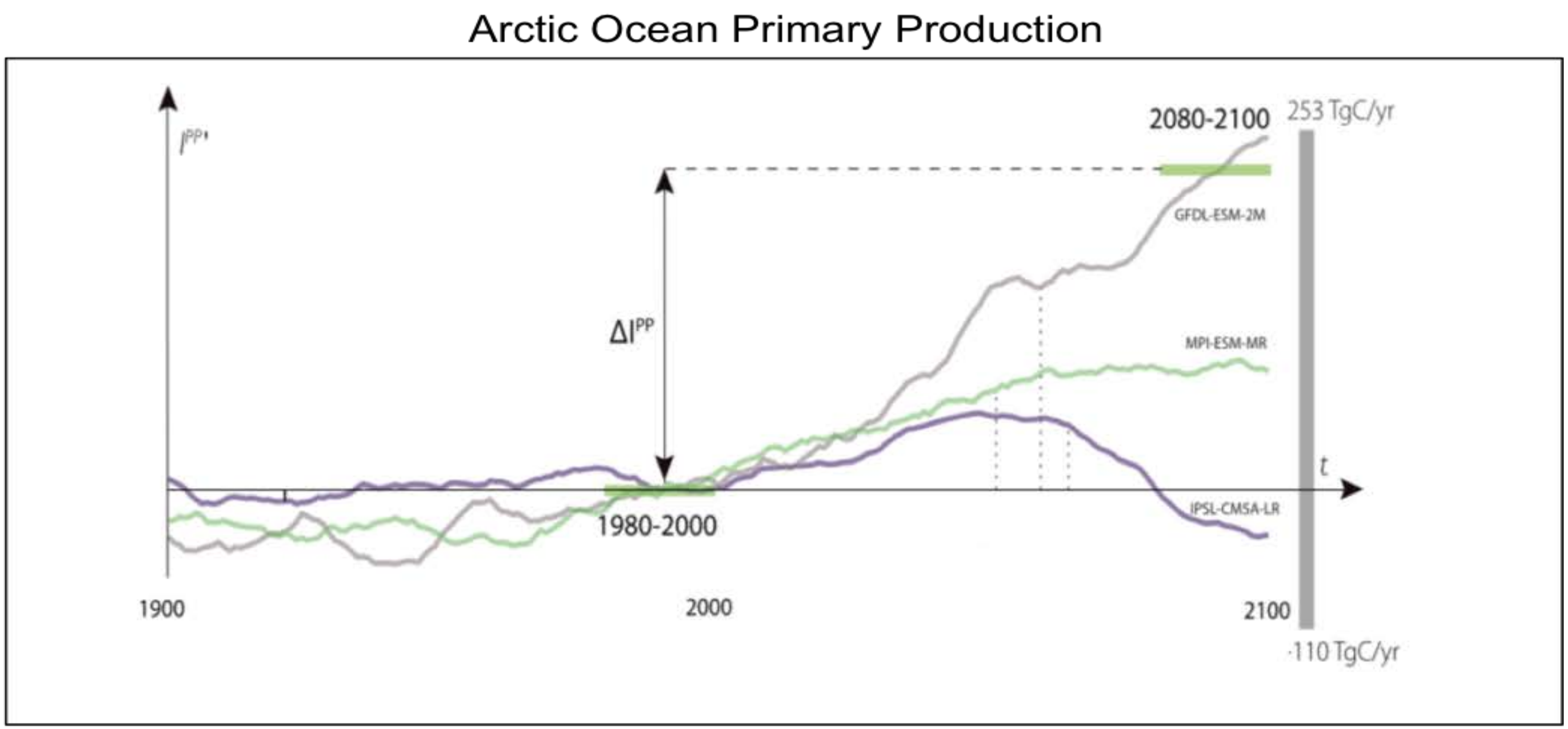



- Arctic Ocean NPP is limited by
  - Light (Sea ice and Arctic winter)
  - Nitrogen

- Arctic Ocean NPP has increased by 57% from 1998 to 2018 (Lewis et al., 2020)

# Projections of Arctic Ocean NPP diverge strongly across climate models

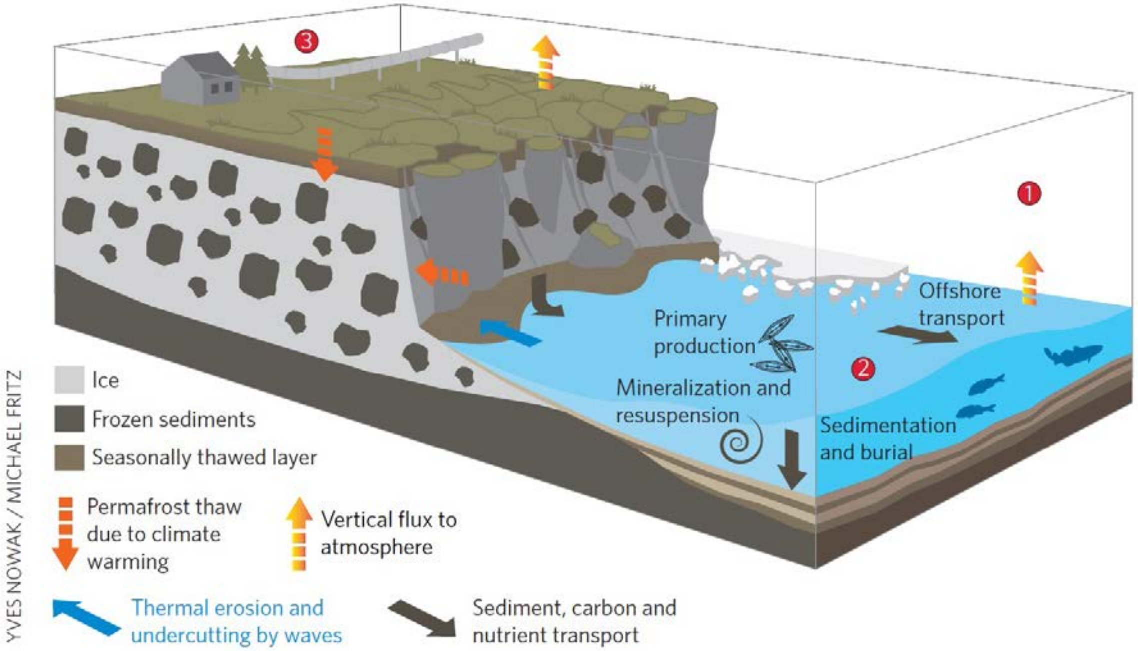
UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH




Vancoppenolle et al. (2013)

# Projections of Arctic Ocean NPP diverge strongly across climate models, **but most of them do not account for terrigenous nutrients from rivers and coastal erosion**

UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH




Fritz et al. (2017)

1) Arctic coastal erosion rates as high as 25 m $yr^{-1}$ (Fritz et al., 2017)

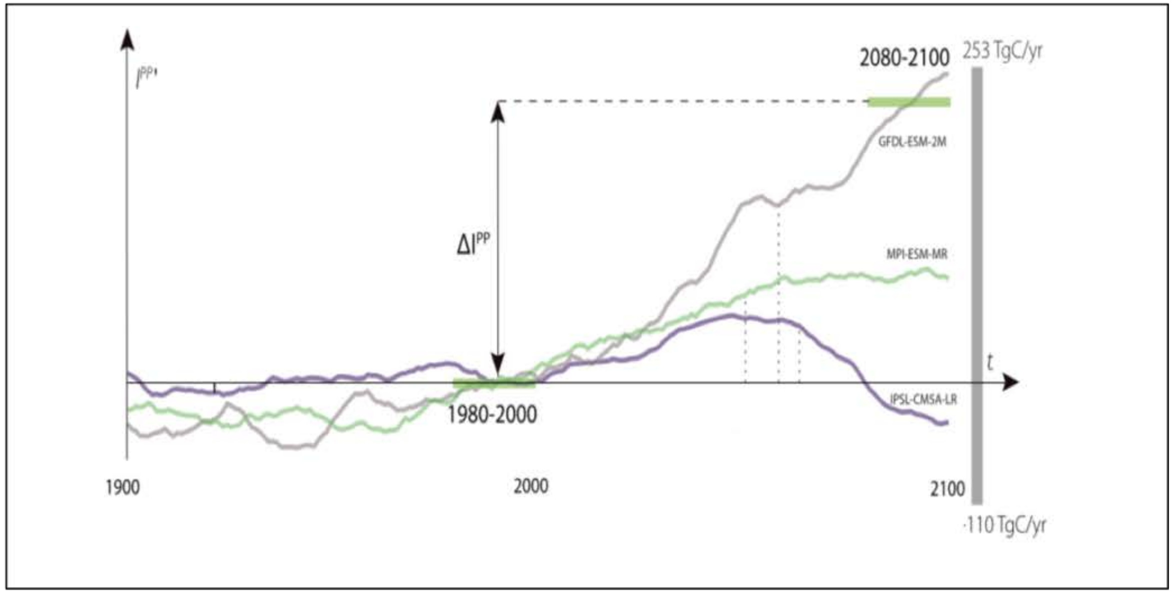
2) Rivers sustain 10% of Arctic Ocean NPP (Le Fouest et al., 2015)

3) Nutrients fluxes from rivers are projected to increase over the 21st century (Frey et al., 2007) and hence increase basin-wide NPP by ~11% (Terhaar et al., 2019)

# Projections of Arctic Ocean NPP diverge strongly across climate models, but most of them do not account for terrigenous nutrients from rivers and coastal erosion

UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH

Arctic Ocean Primary Production




Vancoppenolle et al. (2013)

1) Arctic coastal erosion rates as high as 25 m $yr^{-1}$ (Fritz et al., 2017)

2) Rivers sustain 10% of Arctic Ocean NPP (Le Fouest et al., 2015)

3) Nutrients fluxes from rivers are projected to increase over the 21st century (Frey et al., 2007) and hence increase basin-wide NPP by ~11% (Terhaar et al., 2019)

**Could terrigenous nutrients explain the divergence of Arctic NPP projections?**

# The Arctic Ocean is strongly exposed to terrigenous nutrients due its geographical situation

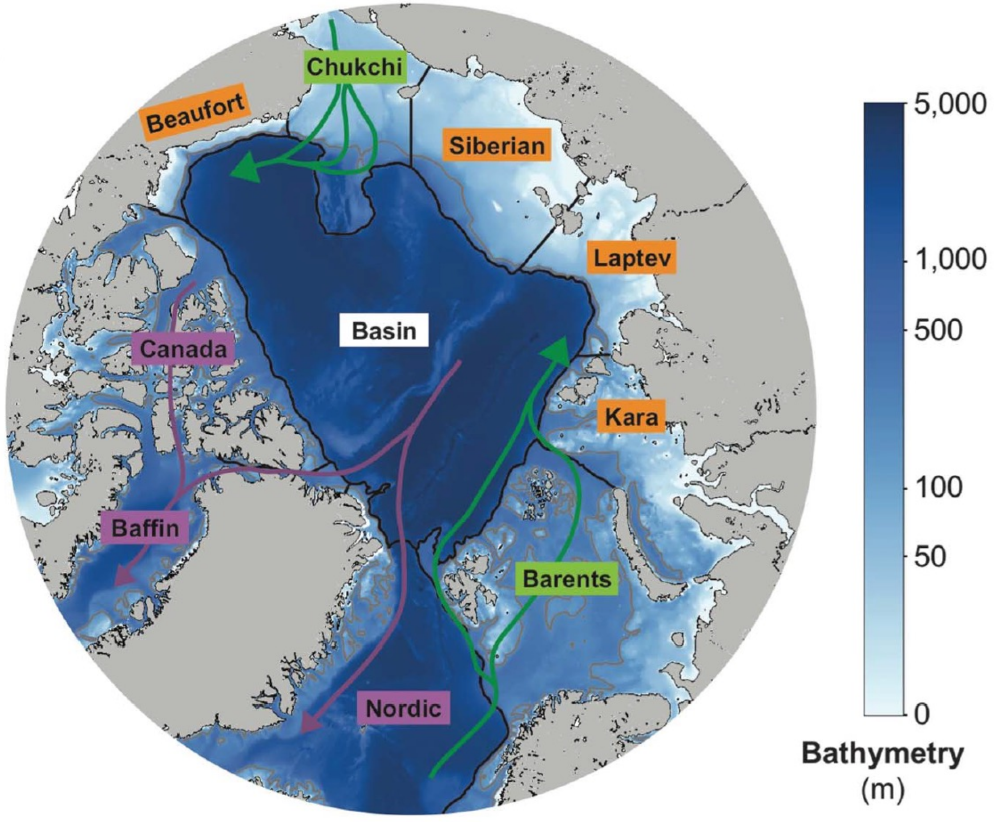


> Arctic Ocean watershed area that is larger than its own area.

> 11% of global river discharge into the Arctic Ocean although it holds only 1% of the global ocean volume

> In addition, the Arctic coastline is eroding fast due to thawing permafrost, providing another important source of terrigenous nutrients

> Arctic shelves represent 18% of global shelf sea volume




(Lewis et al., 2020)

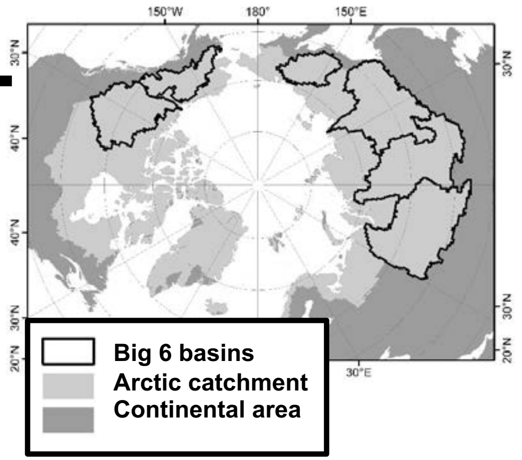
# We derived spatially and temporally resolved carbon and nutrient fluxes from rivers and coastal erosion

**Riverine C, N, P, Si inputs**

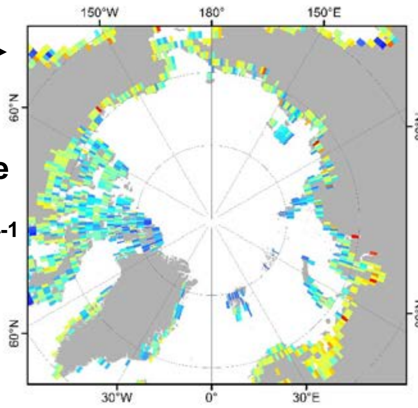
Observed fluxes from big 6 Arctic Rivers (ArticGro[1])

Spatial extrapolation based on catchment properties

Monthly fluxes as function of monthly discharge (Dai & Trenberth 2002)




**Here: month June**




**kt DIN yr$^{-1}$**
**1400**
**0**

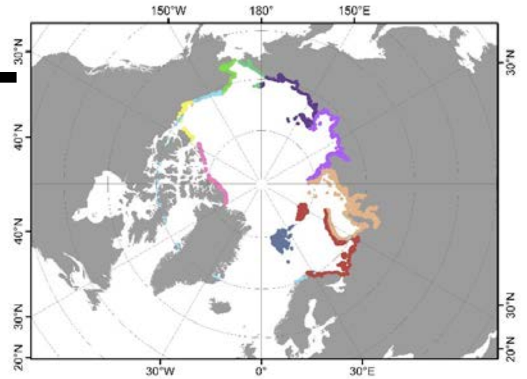
[1]Arctic Great Rivers Observatory (Holmes et al., 2018)

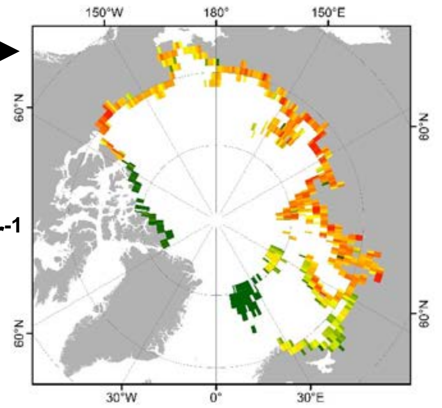
**Coastal Erosion of C, N, P**

Observed erosion rates and org. C content (ACD[2])

Used average C:N ratios for different coastal stretches

Erosional fluxes seasonally divided based on observations




**kt N yr$^{-1}$**
**40**
**0**

[2]Arctic Coastal Dynamics Database (Lantuit et al., 2012)

Terhaar et al. (2021)

# We derived spatially and temporally resolved carbon and nutrient fluxes from rivers and coastal erosion

UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH

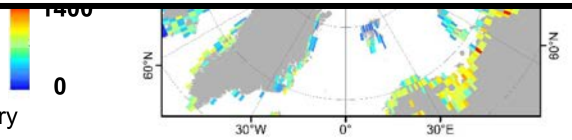
**Riverine C, N, P, Si inputs**

**Coastal Erosion of C, N, P**

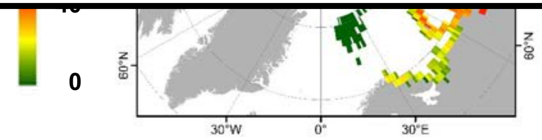
## The full dataset is freely available on SEANOE:

## Gridded carbon and nitrogen land-ocean fluxes north of 60° N from rivers and coastal erosion

## [https://doi.org/10.17882/76983](https://doi.org/10.17882/76983).




[1]Arctic Great Rivers Observatory (Holmes et al., 2018)

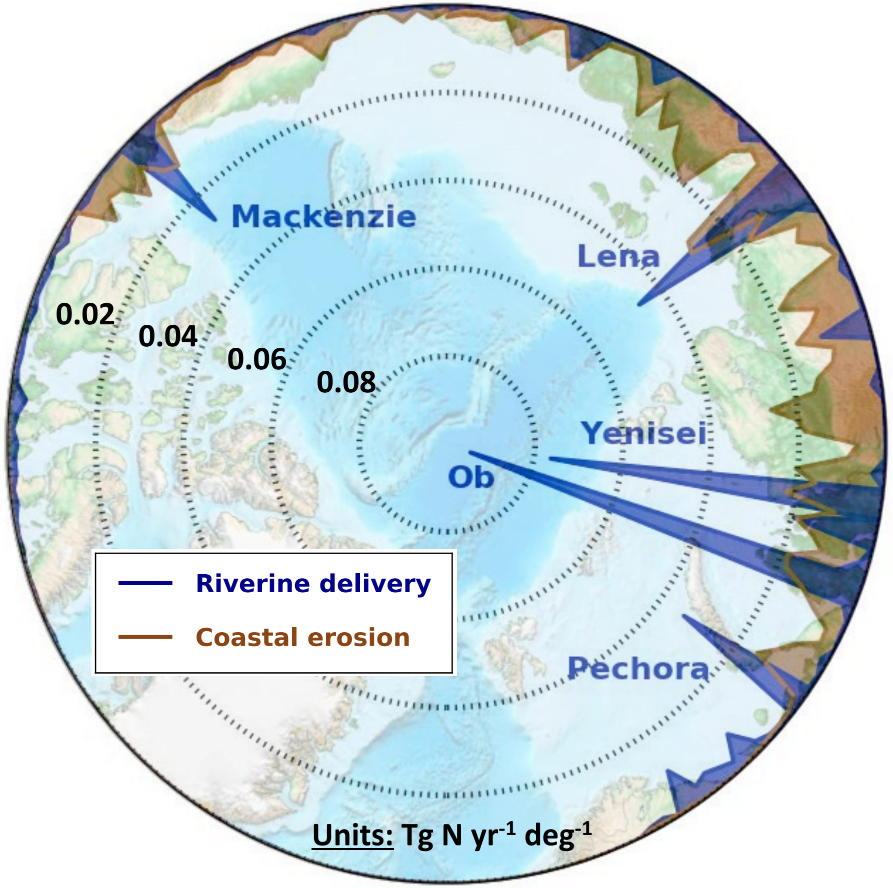


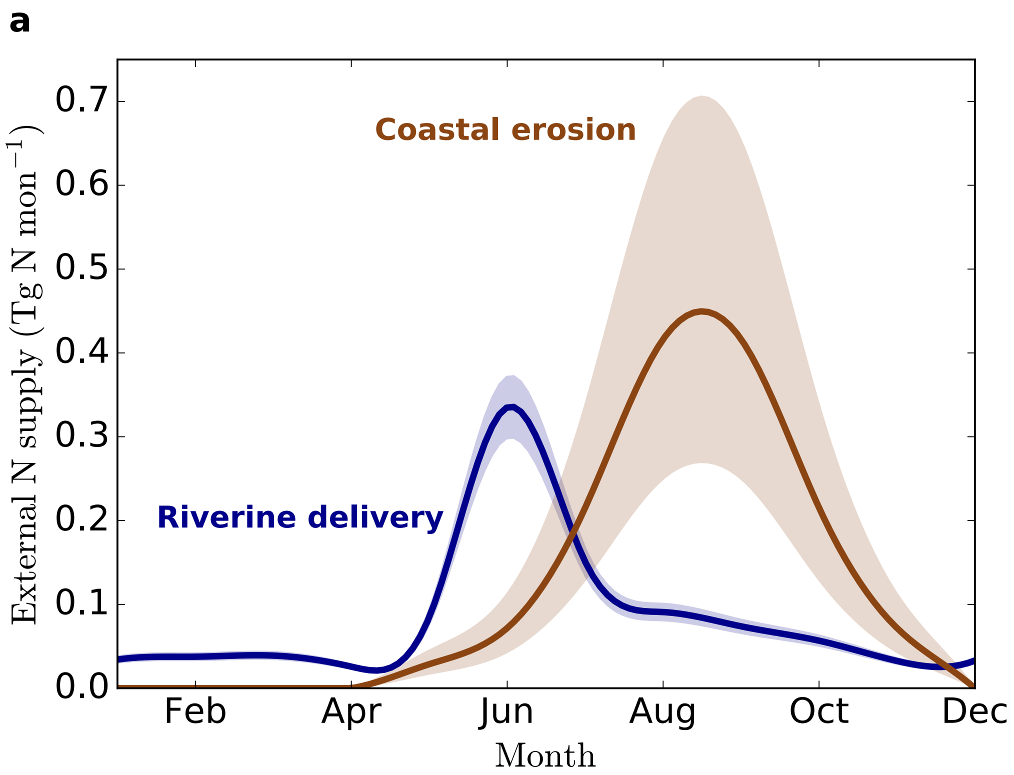

[2]Arctic Coastal Dynamics Database (Lantuit et al., 2012)

Terhaar et al. (2021)

# We derived spatially and temporally resolved carbon and nutrient fluxes from rivers and coastal erosion

UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH




Terhaar et al. (2021)

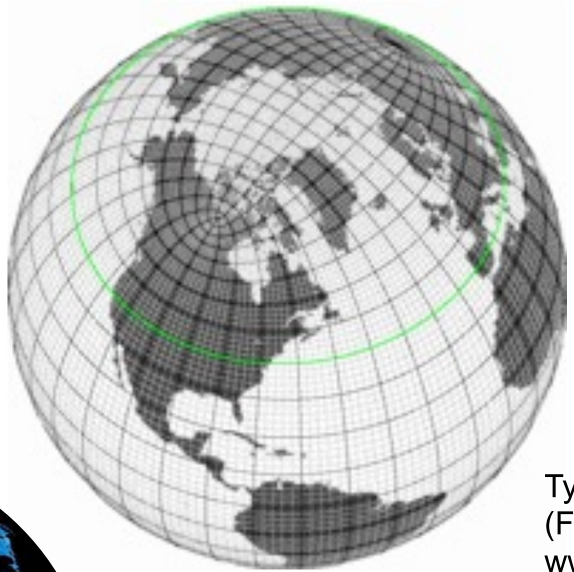
# The impact of terrigenous nutrients on Arctic Ocean NPP is quantified using a high-resolution ocean-biogeochemical model (NEMO-PISCES)

UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH

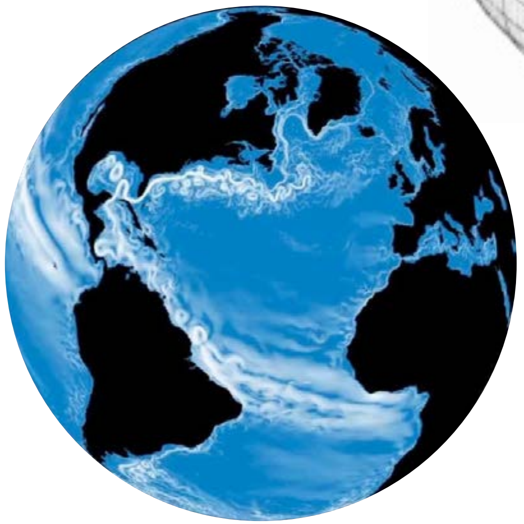
- Discretization of Navier-Stokes equations
- Sea Ice model LIM
- Atmospheric forcing:
  - Historical reanalysis (DFS 4.2/ DFS 4.4)

- Nominal horizontal resolution 0.25°

(ca. 14 km in the Arctic Ocean)



Typical ORCA grid (Figure from www.geomar.de)



Simulated surface velocity www.nemo-ocean.eu

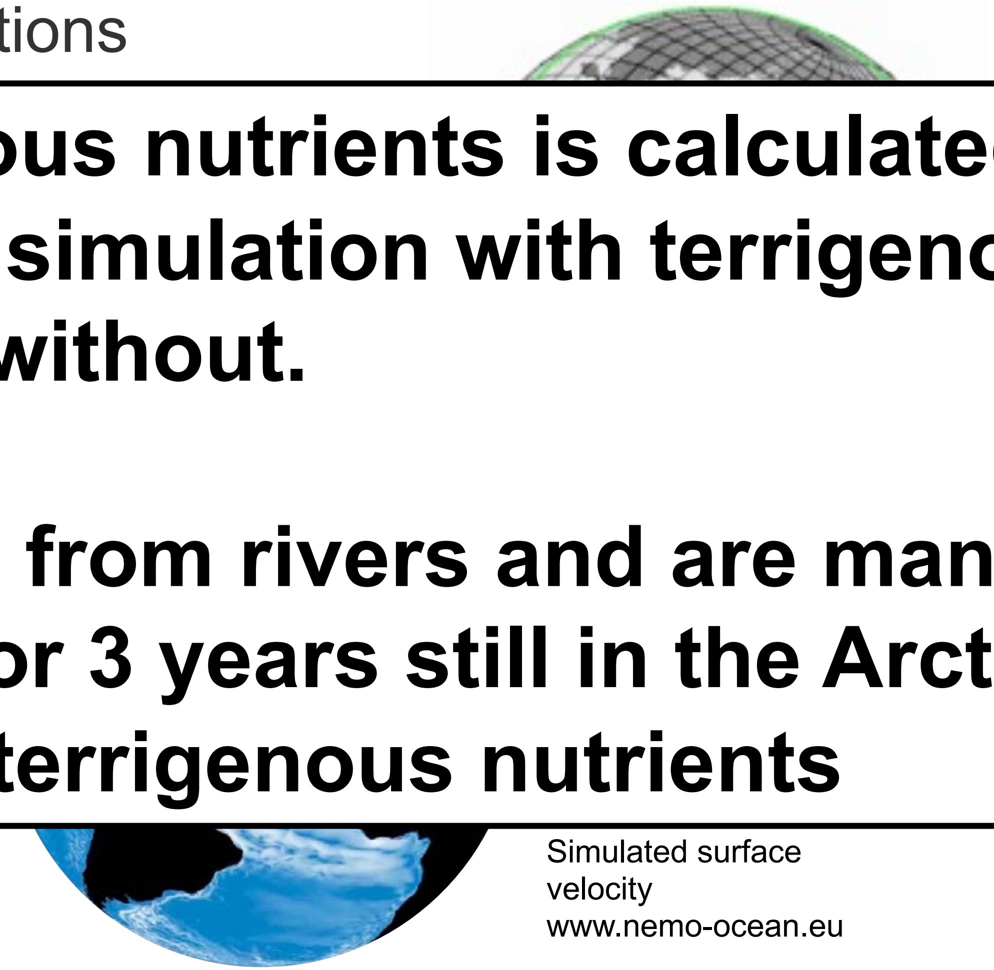
## The impact of terrigenous nutrients on Arctic Ocean NPP is quantified using a high-resolution ocean-biogeochemical model (NEMO-PISCES)

UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH

- Discretization of Navier-Stokes equations

**NPP sustained by terrigenous nutrients is calculated as the difference between the simulation with terrigenous nutrient input and the one without.**

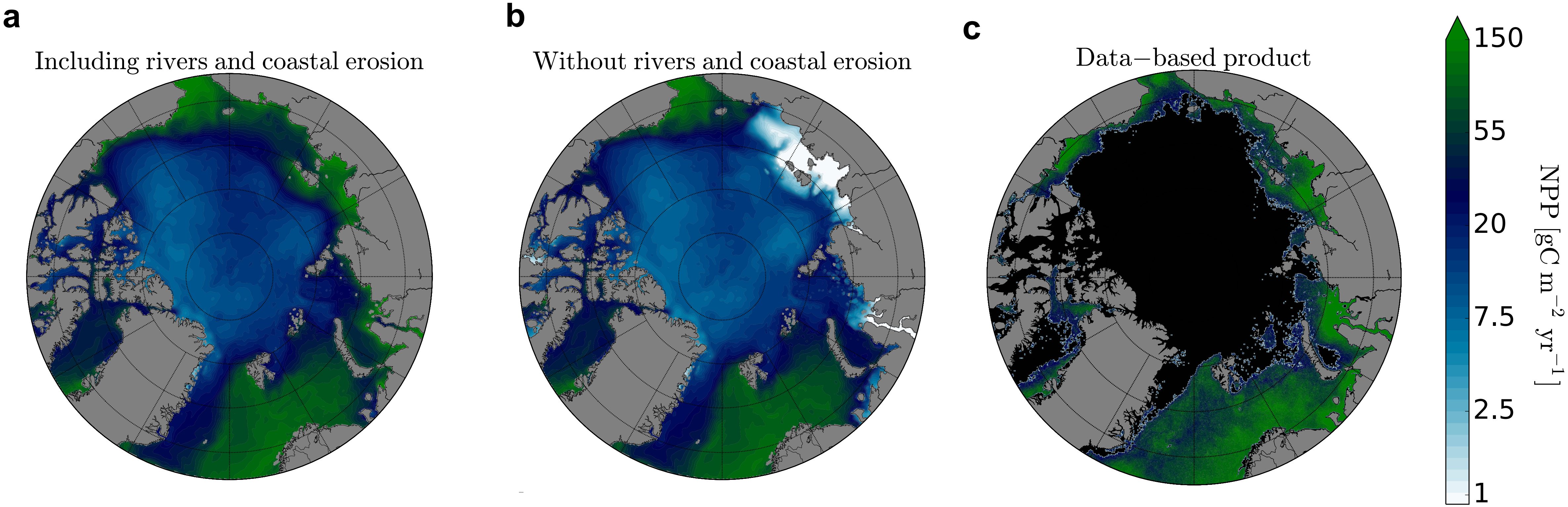
**Hence, nutrients that come from rivers and are many times recycled and after 2 or 3 years still in the Arctic Ocean are still counted as terrigenous nutrients**



Simulated surface velocity
www.nemo-ocean.eu

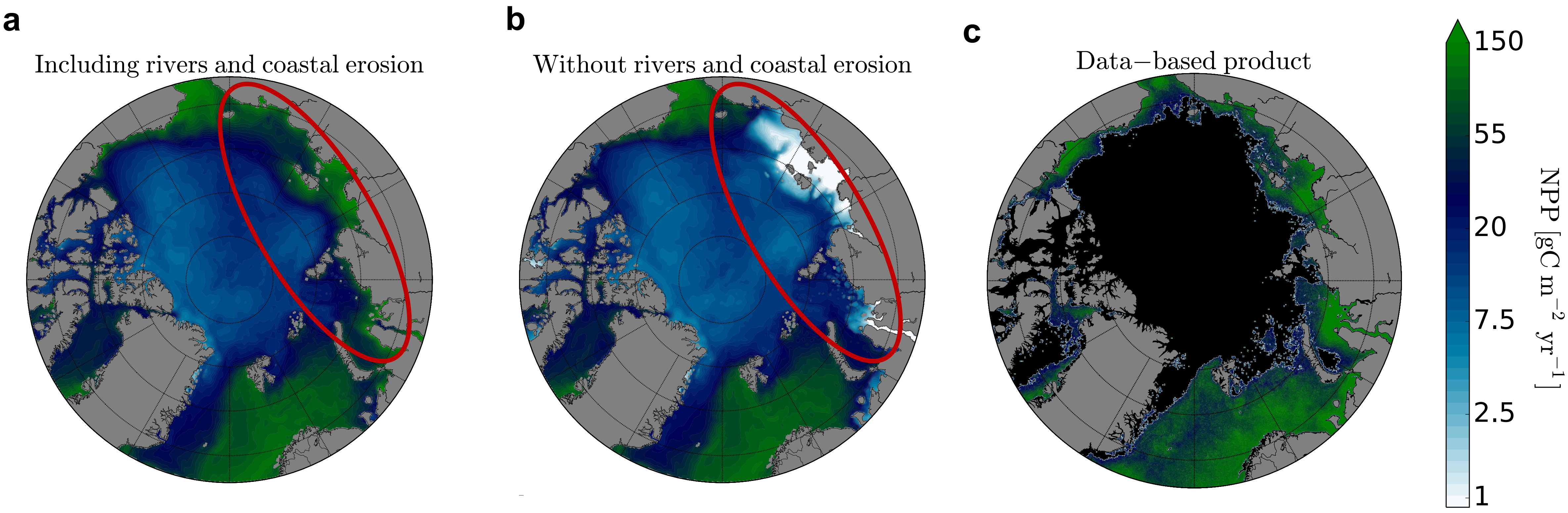
# Around one third of Arctic Ocean NPP is found to be sustained by terrigenous nutrients

UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH




Terhaar et al. (2021)

# Around one third of Arctic Ocean NPP is found to be sustained by terrigenous nutrients

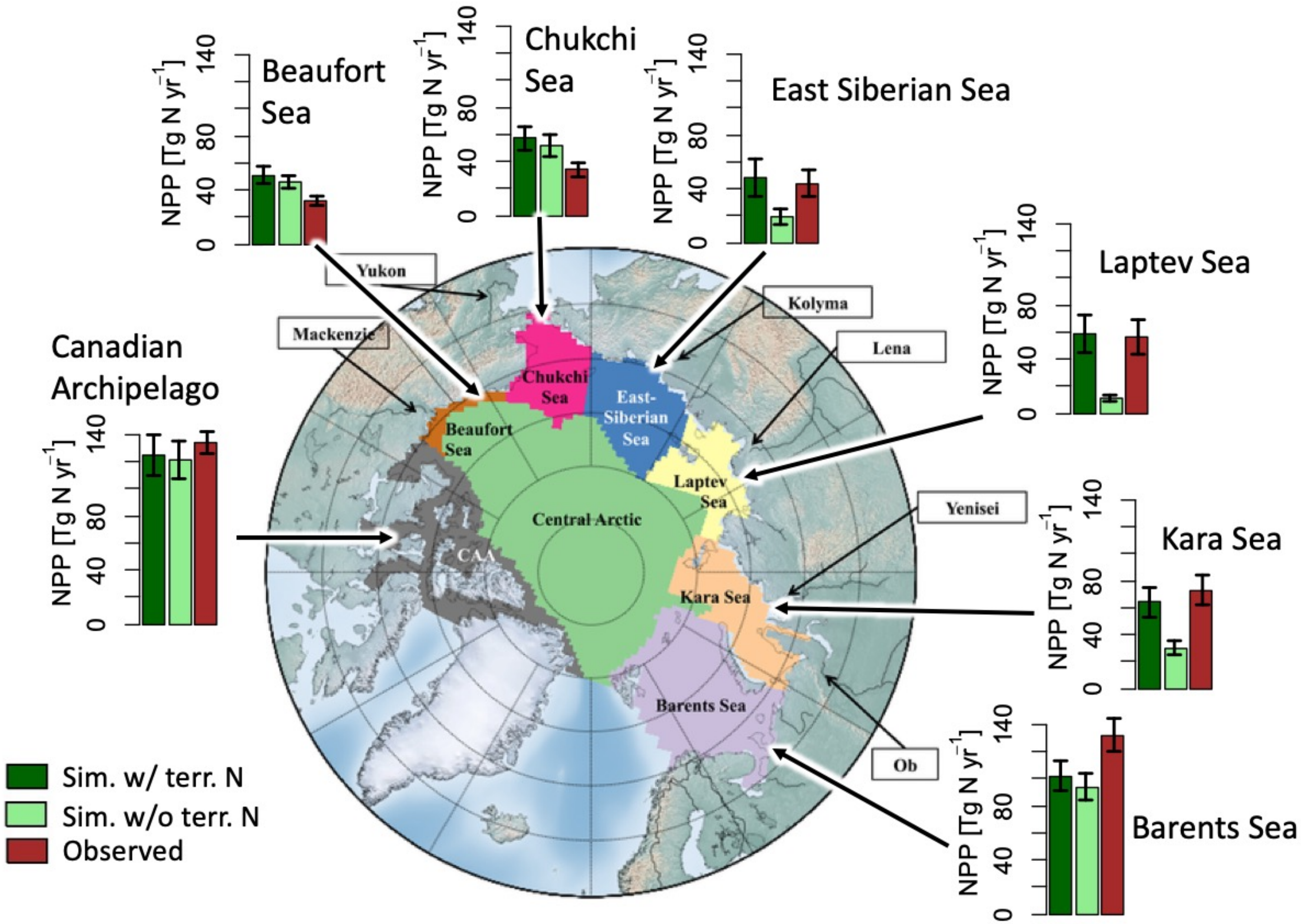



Terhaar et al. (2021)

# Simulated NPP is far too low without terrigenous N inputs

UNIVERSITÄT BERN

OESCHGER CENTRE CLIMATE CHANGE RESEARCH



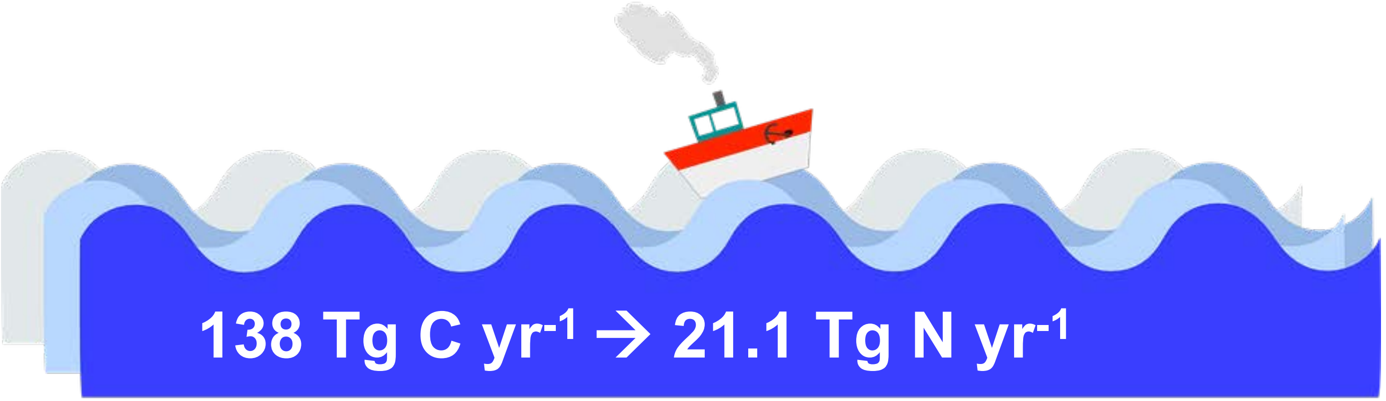

Terhaar et al. (2021)

# NPP driven by terrigenous nitrogen is 8 times larger than the terrigenous nitrogen delivery

UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH

## Terrigenous supply of nitrogen


## NPP in the Arctic Ocean driven by terrigenous nitrogen

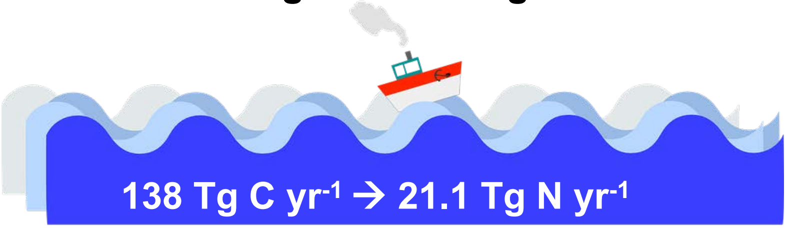


# Terrigenous nutrients are recycled on average about 8 times in the Arctic Ocean before being exported

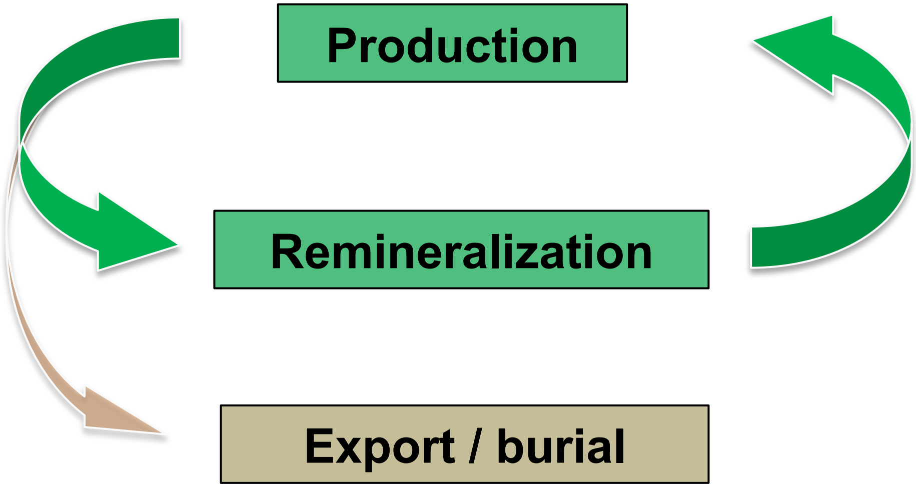
UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH

**Terrigenous supply of nitrogen**


**NPP in the Arctic Ocean driven by terrigenous nitrogen**



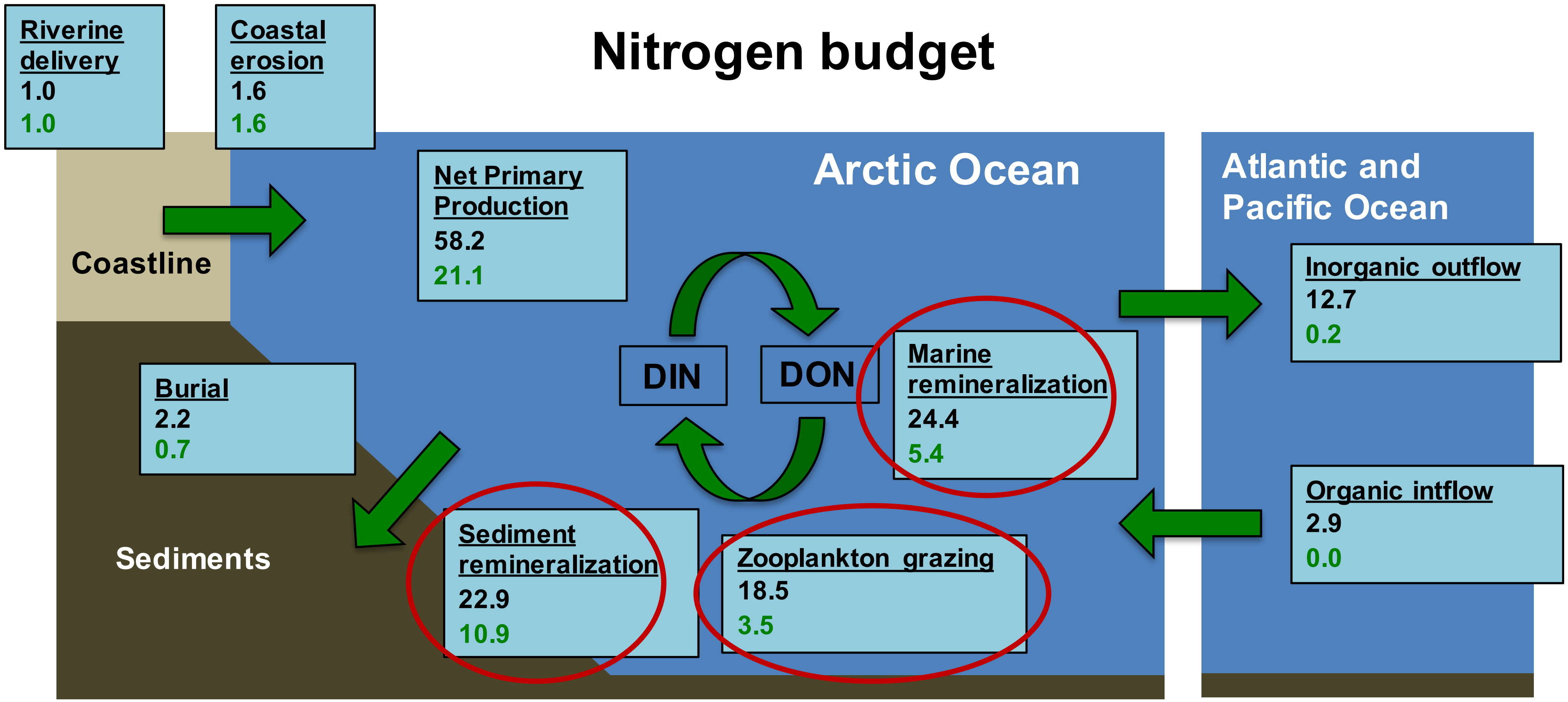

## Recycling of nutrients in the surface ocean




Previous estimates in the Canadian Arctic Archipelago show recycling rates of 0.5-3.2
(Smith et al.1997; Tremblay et al. 2006; Garneau et al.2007)

# The remineralization is largely occurring within the sediments

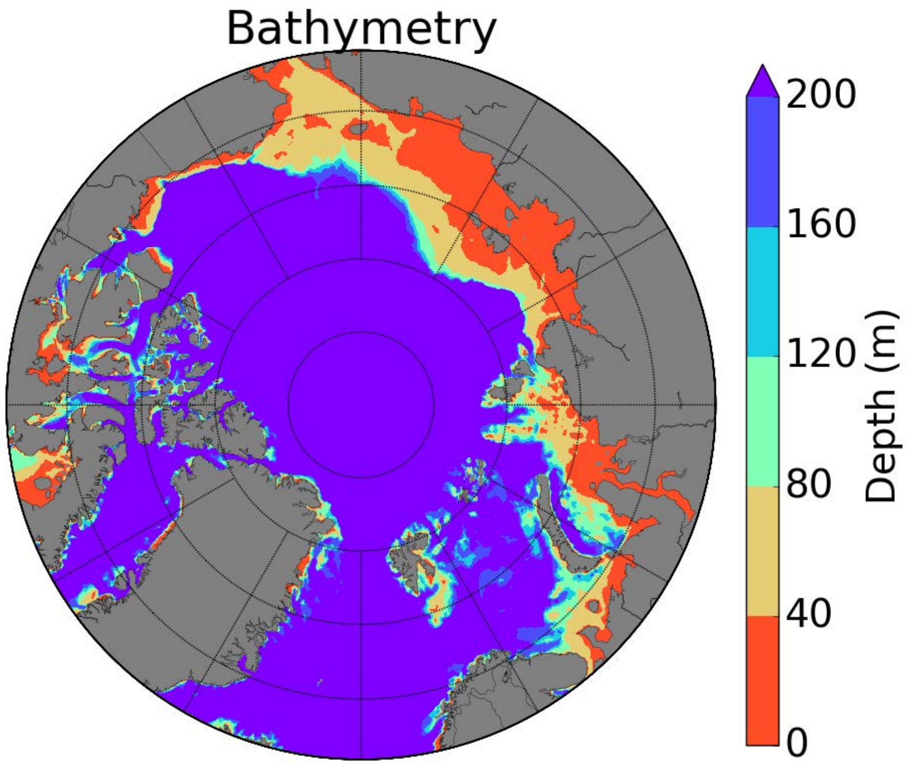
UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH

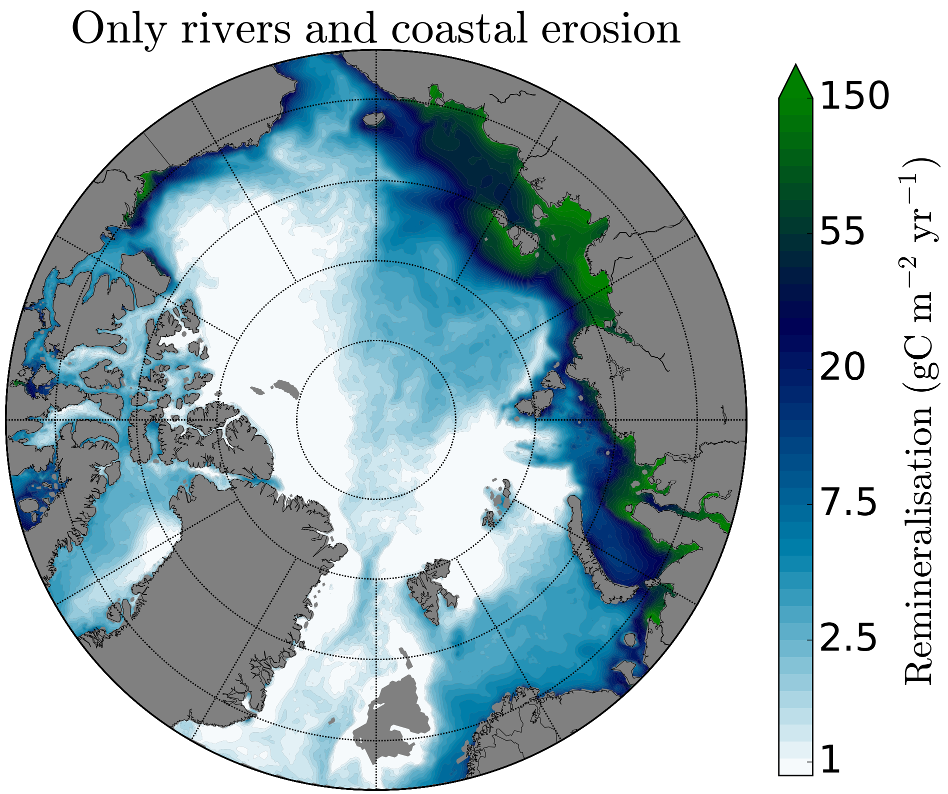



Terhaar et al. (2021)

# Remineralization is mainly occurring on shallow Arctic shelf seas

UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH

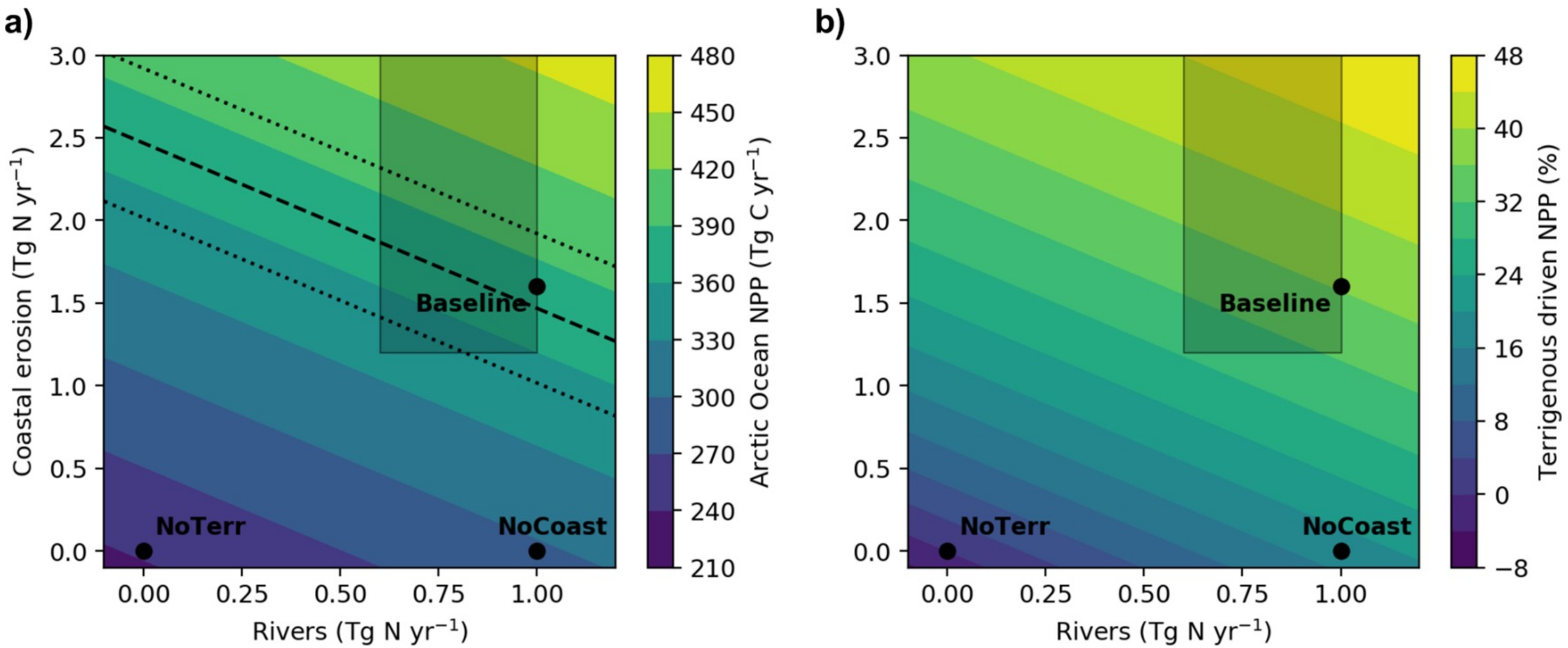



Terhaar et al. (2021)

# The results are robust when considering a wide range of remineralization rates and uncertainties in terrigenous nitrogen quantities

UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH



# Take home messages

UNIVERSITÄT
BERN

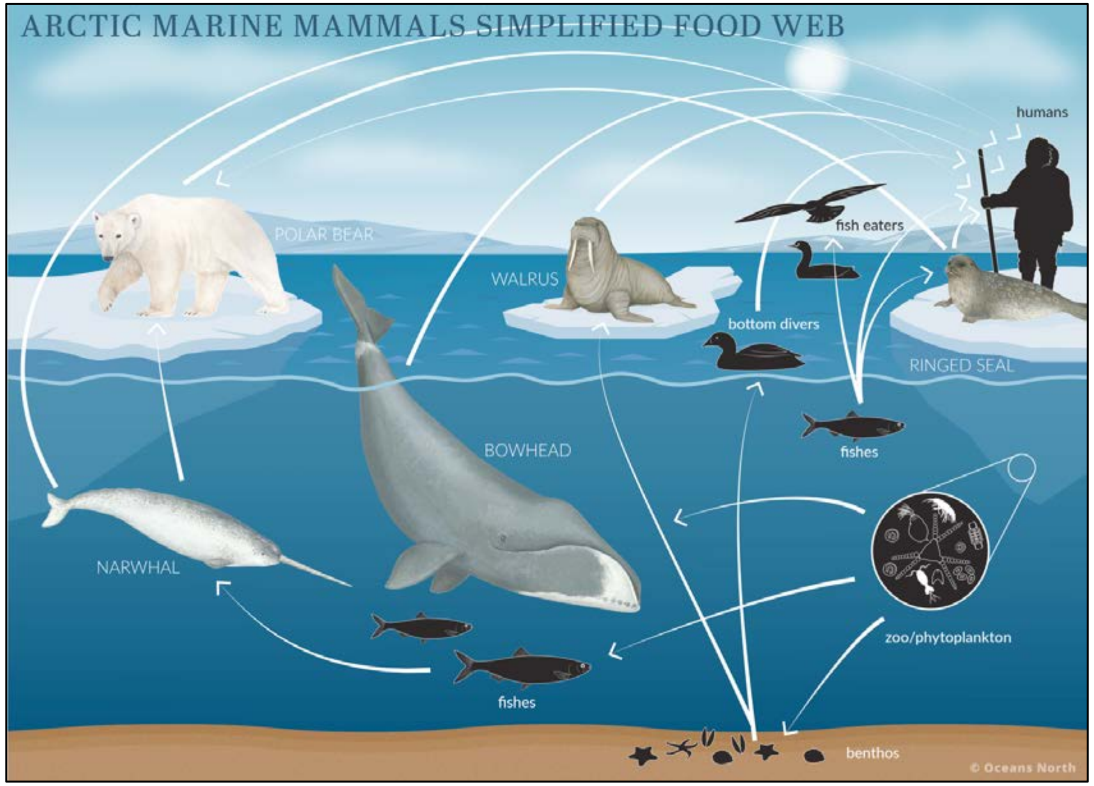
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH

1) Terrigenous nutrients are one of the main drivers of Arctic Ocean primary production

2) Terrigenous nutrients are recycled on average 7 times before leaving the upper Arctic Ocean

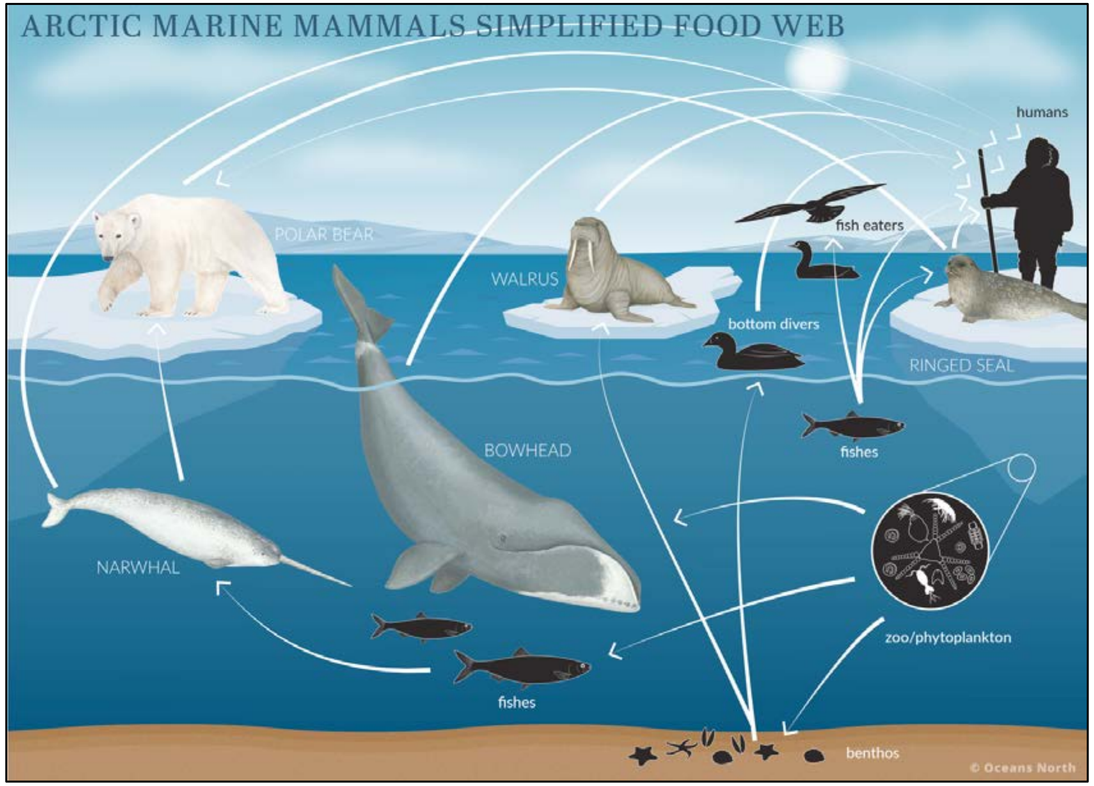
3) Most of the remineralization of organic matter occurs in the shallow Arctic Ocean sediments

# Summary




1) Ocean acidification is extremer than previously expected and thus endangers the Arctic Ocean ecosystem even more ☹

## Summary




1) Ocean acidification is extremer than previously expected and thus endangers the Arctic Ocean ecosystem even more ☹

2) Increasing terrigenous nutrients may lead to a future increase in Arctic Ocean NPP and thus increasing the food availability in the Arctic Ocean ☺