19th ASOF-ISSG Meeting and Workshop

Ocean-ice-atmosphere interaction during the Arctic Atlantification

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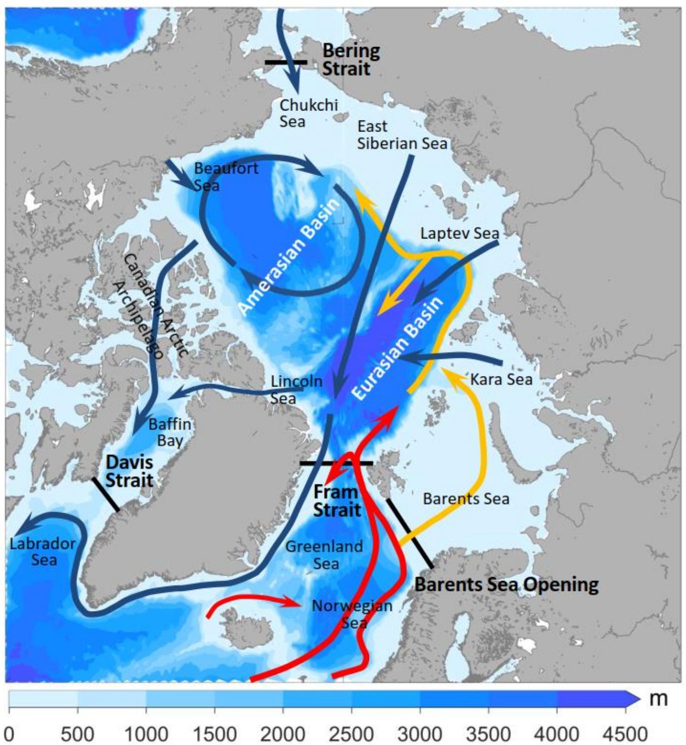
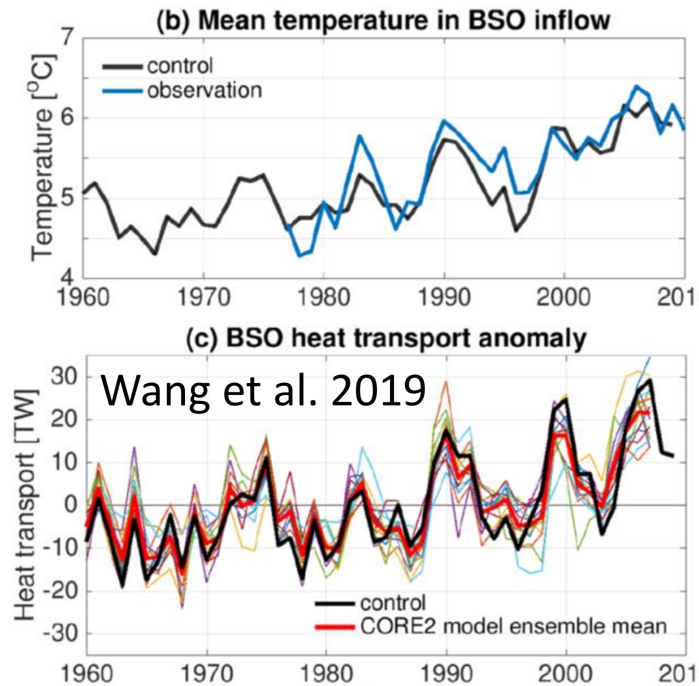
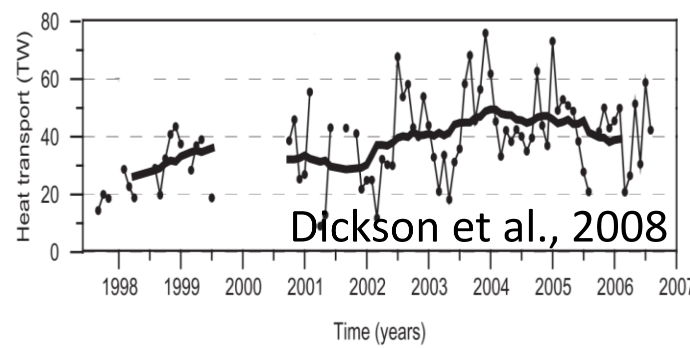
Background

AW warming and increased ocean heat transport through Barents Sea Opening (BSO)





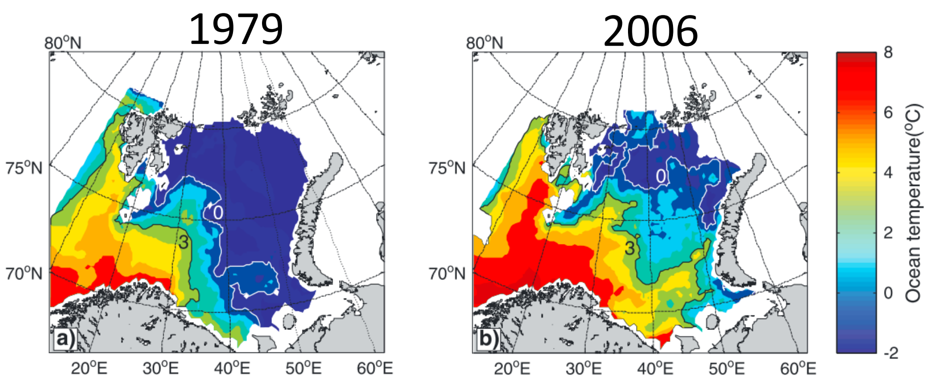
Wang et al. 2019



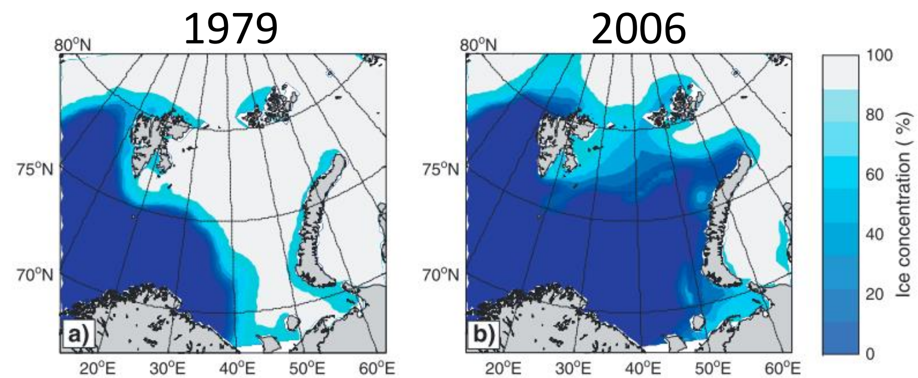
Dickson et al., 2008

Background

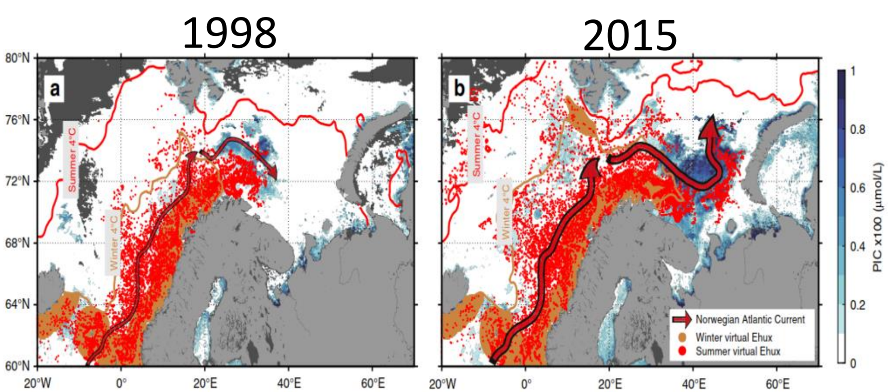
Atlantification in the Barents Sea: ocean warming, sea ice decline, marine ecosystem shift



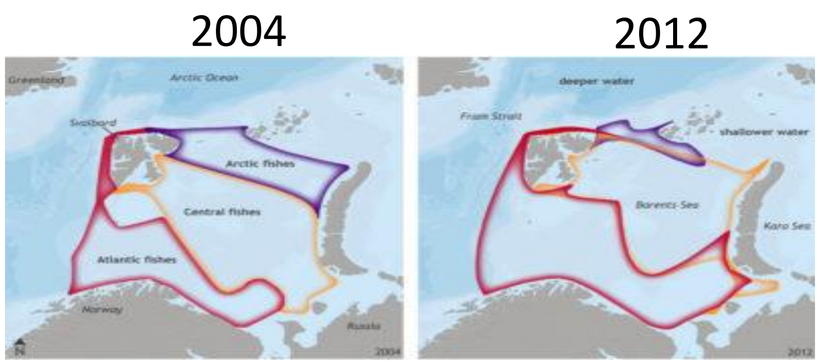
Ocean warming (Smedsrud et al., 2013)



Winter sea ice decline (Smedsrud et al., 2013)



Ehux poleward expansion (Oziel et al., 2020)

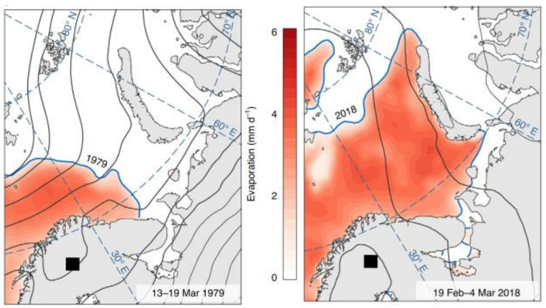


Borealization of fish communities (Fossheim et al., 2015)

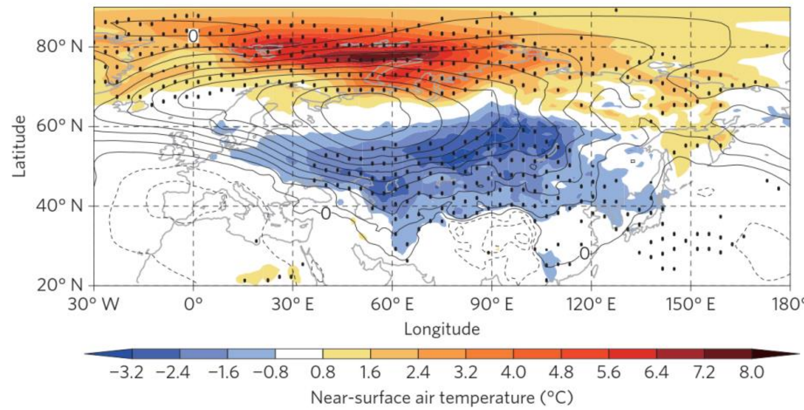
Background

Barents Sea Atlantification affects the weather and climate of the Eurasian continent through ocean-ice-atmosphere interaction.

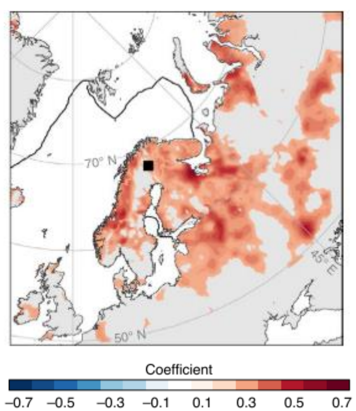
1979 2018



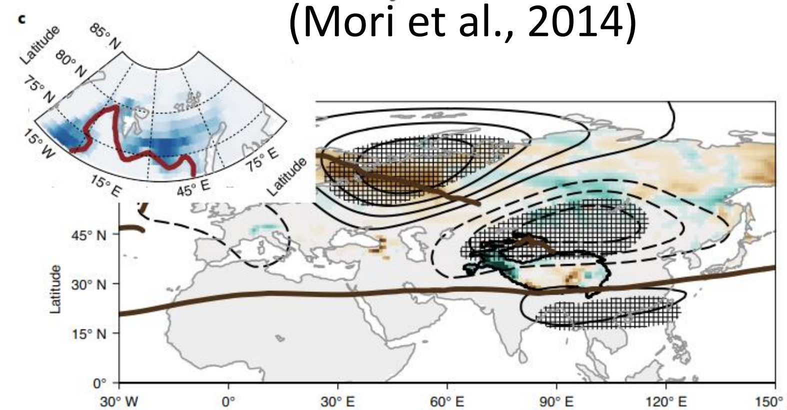
Evaporation



Sea ice and Eurasian cold winter links
(Mori et al., 2014)



Evaporation and snowfall links
(Bailey et al., 2021)



Sea ice and aerosol in the Tibetan Plateau links
(Li et al., 2020)

Questions

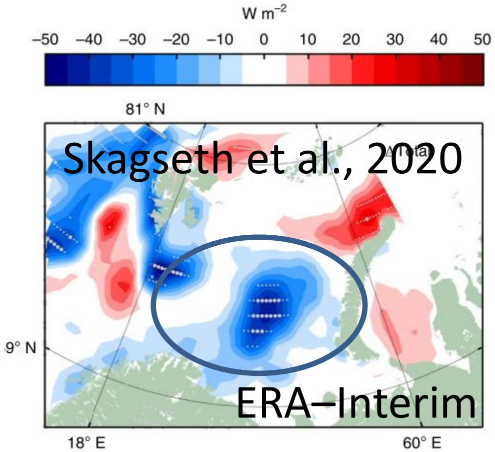
How does ocean-ice-atmosphere interaction change during Arctic Atlantification?
How will Arctic ocean-ice-atmosphere interaction change in the future?
What is the role of ocean-ice-atmosphere interaction in future Arctic Ocean warming?

Datasets

- ORAS5: Ocean ReAnalysis System 5
- SODA3: Simple Ocean Data Assimilation ocean reanalysis
- ERA5: ECMWF Reanalysis v5
- NSIDC: National Snow and Ice Data Center
- CMIP6: Coupled Model Intercomparison Project Phase 6

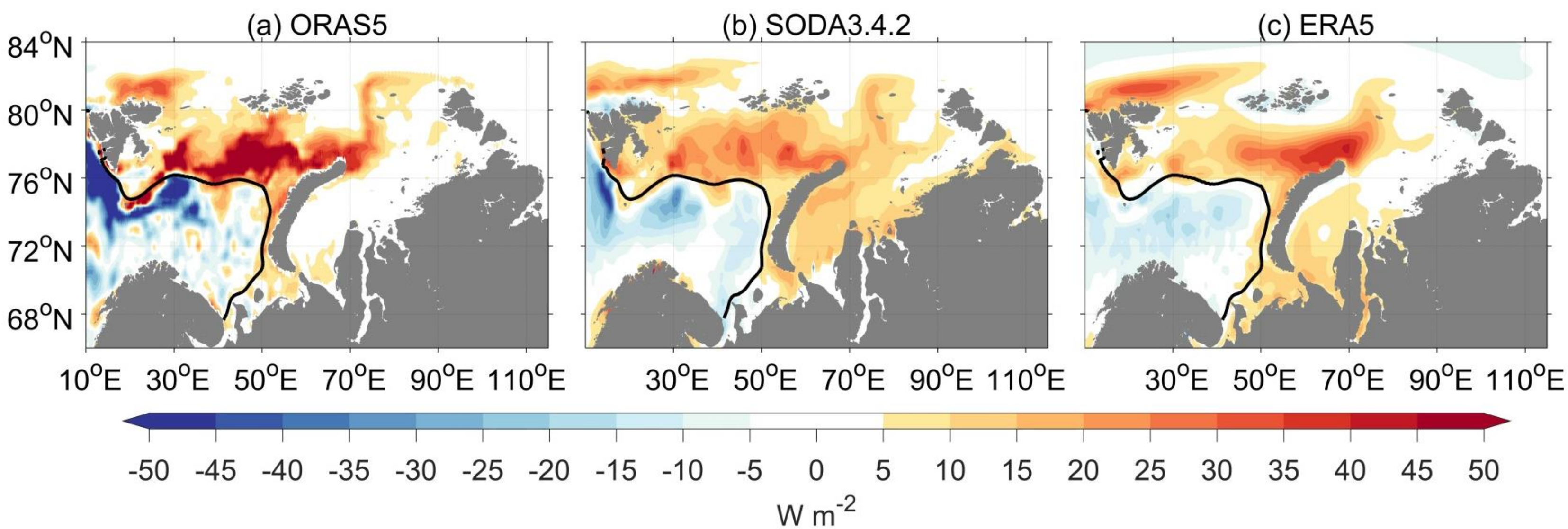
No.	Model name	Institution ID
1	CanESM5	CCCma
2	CESM2	NCAR
3	CESM2-WACCM	NCAR
4	CNRM-CM6-1	CNRM-CERFACS
5	EC-Earth3-Veg	EC-Earth-Consortium
6	FIO-ESM-2-0	FIO-QLNM
7	GFDL-CM4	NOAA-GFDL
8	IPSL-CM6A-LR	IPSL
9	MPI-ESM1-2-HR	MPI-M
10	MPI-ESM1-2-LR	MPI-M
11	NorESM2-LM	NCC
12	UKESM1-0-LL	MOHC

Changes in annual mean sea surface heat flux



Changes in annual mean sea surface heat flux between the periods of 2004-2018 and 1985-1999

Upward sea surface heat flux is positive.



- Less ocean heat release in ice-free regions and more ocean heat release in ice-covered region.

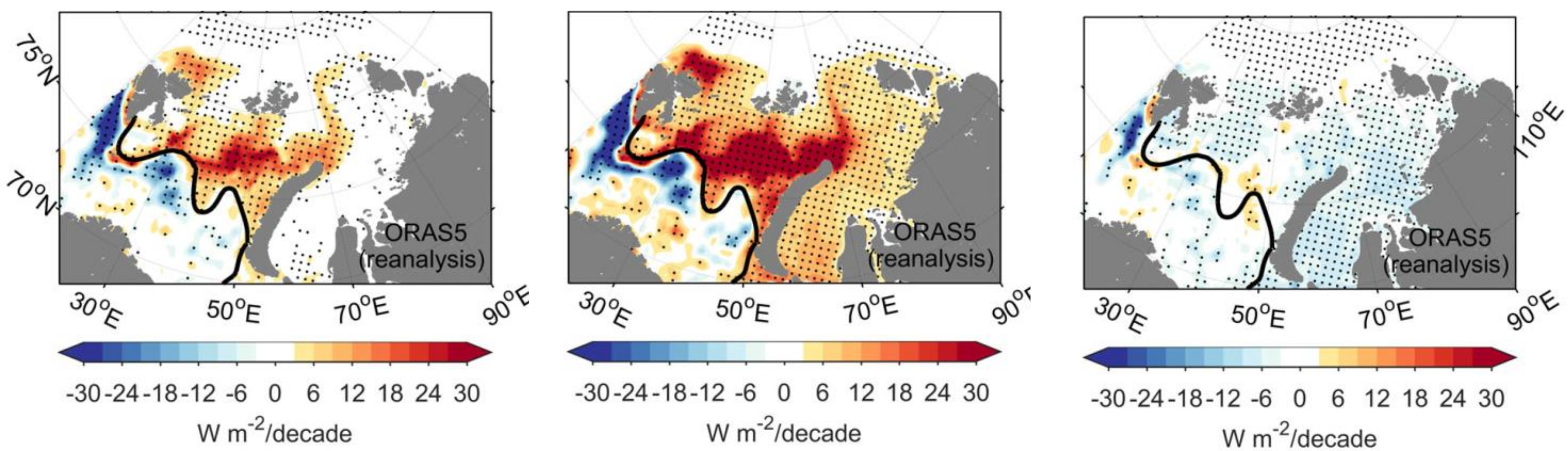
Linear trends of sea surface heat flux

The linear trends of sea surface heat flux during 1979-2018

Annual mean

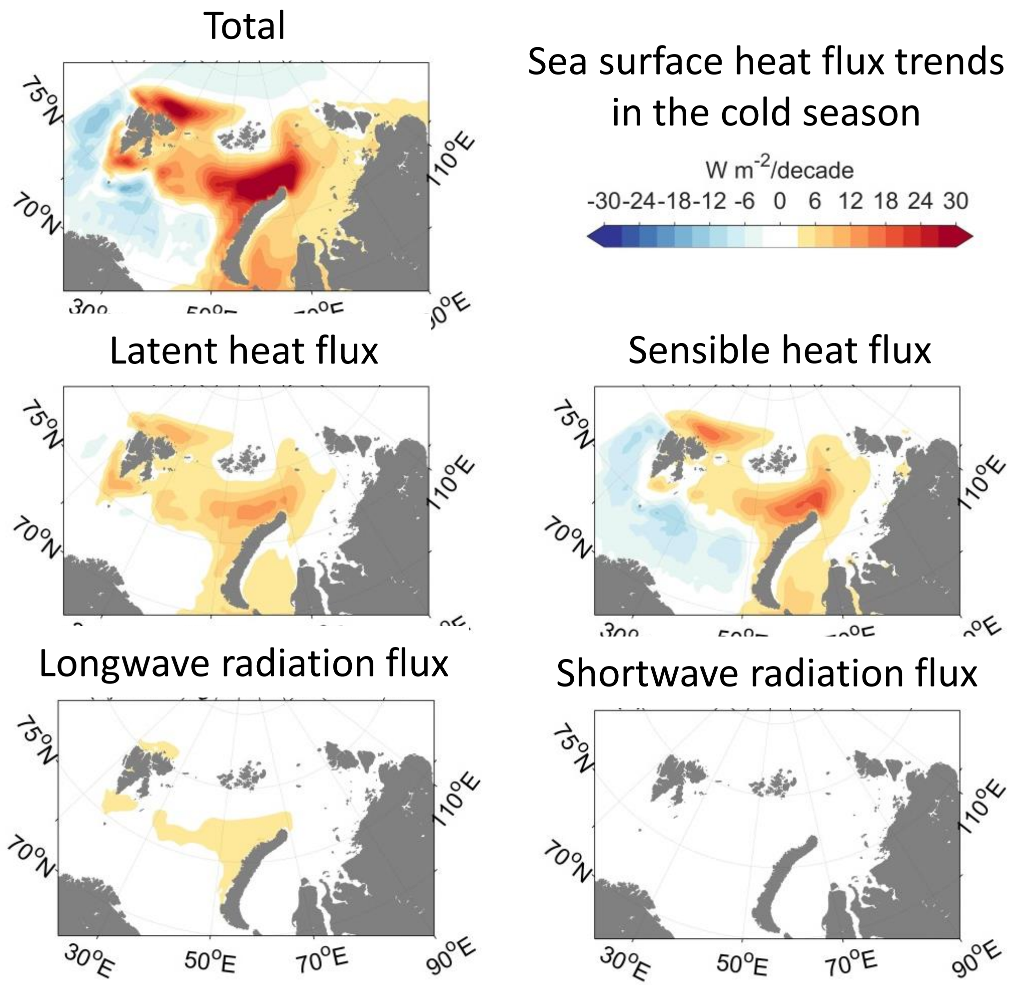
Cold season (October–March)

Warm season (April–September)



- The annual mean trends are mainly from the trends in the cold season.

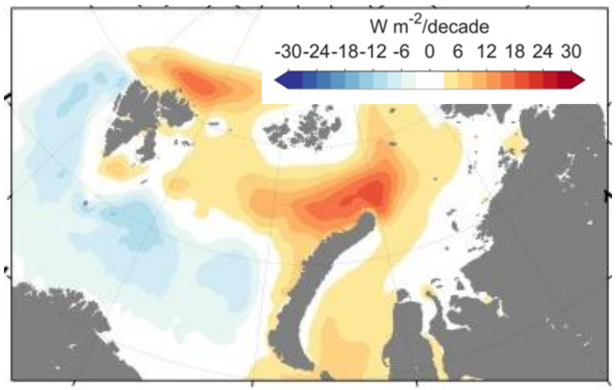
Linear trends of sea surface heat flux



- Positive trends in the ice-covered regions are mainly from latent and sensible heat flux.
- Negative trends in ice-free regions are mainly from sensible heat flux.

Why does sensible heat flux show negative trends in ice-free regions?

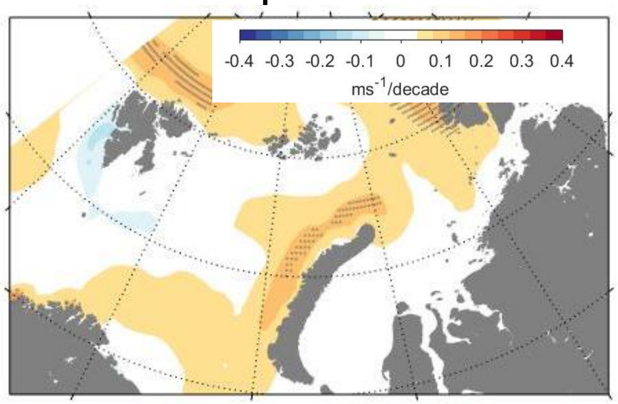
Sensible heat flux trend



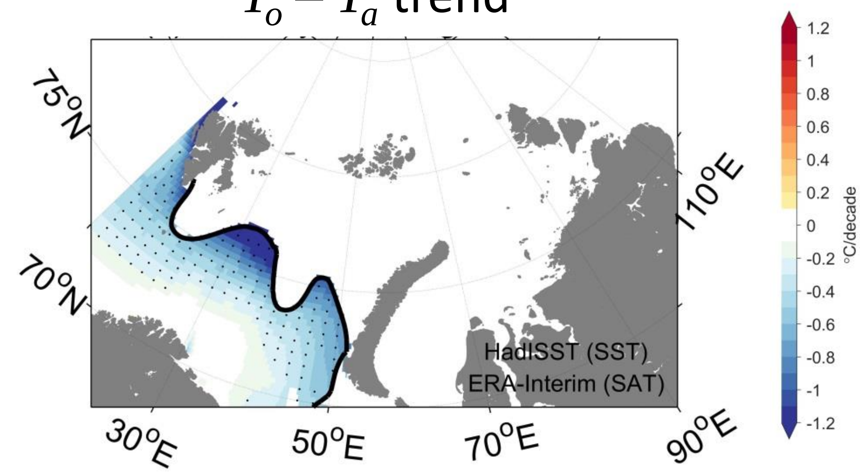
Surface sensible heat flux:

$$Q^{sens} = \rho_a c_p C_T u_{wind}(T_o - T_a)$$

Wind speed trend

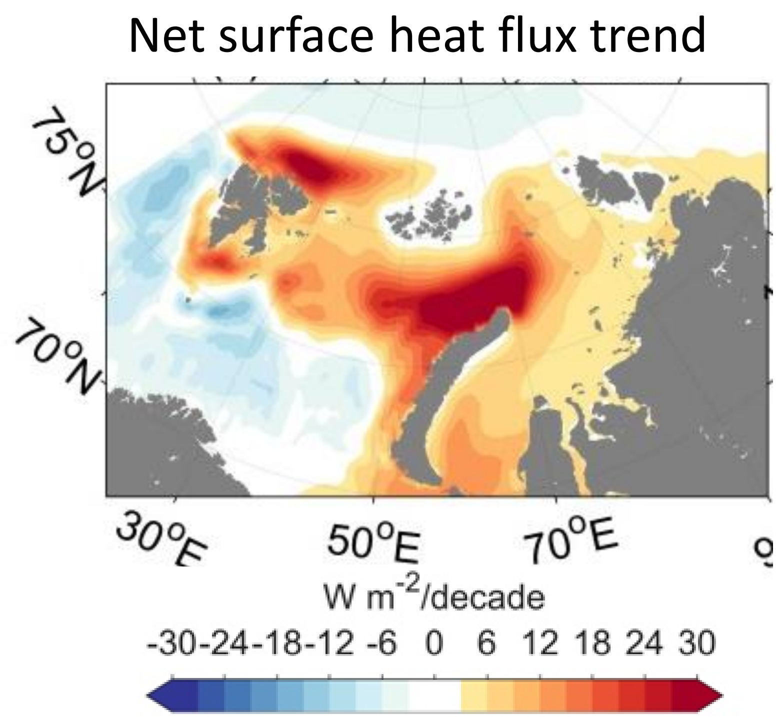


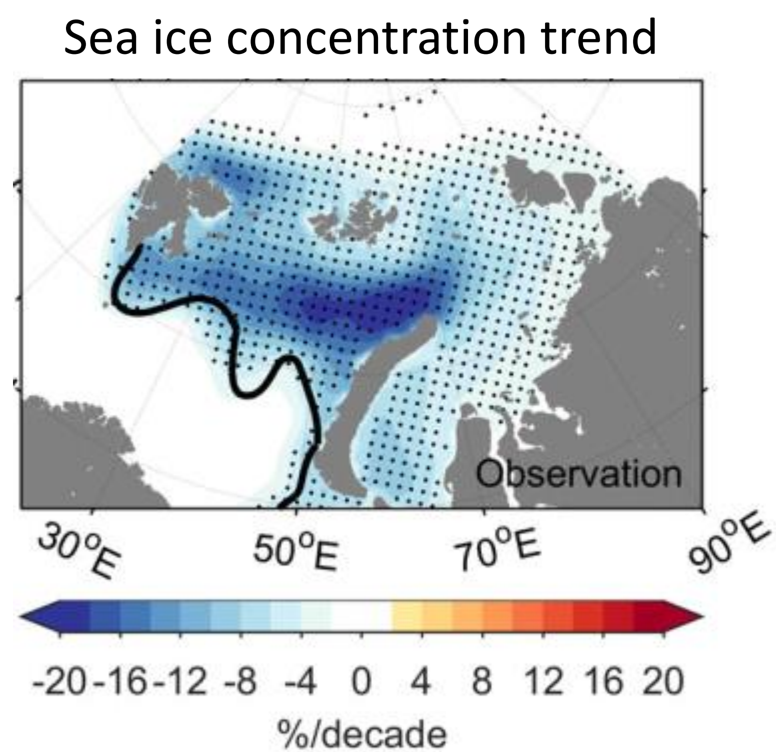
$T_o - T_a$ trend



- Negative trends in ice-free regions are mainly because the near-surface air has a stronger warming trend than the ocean.

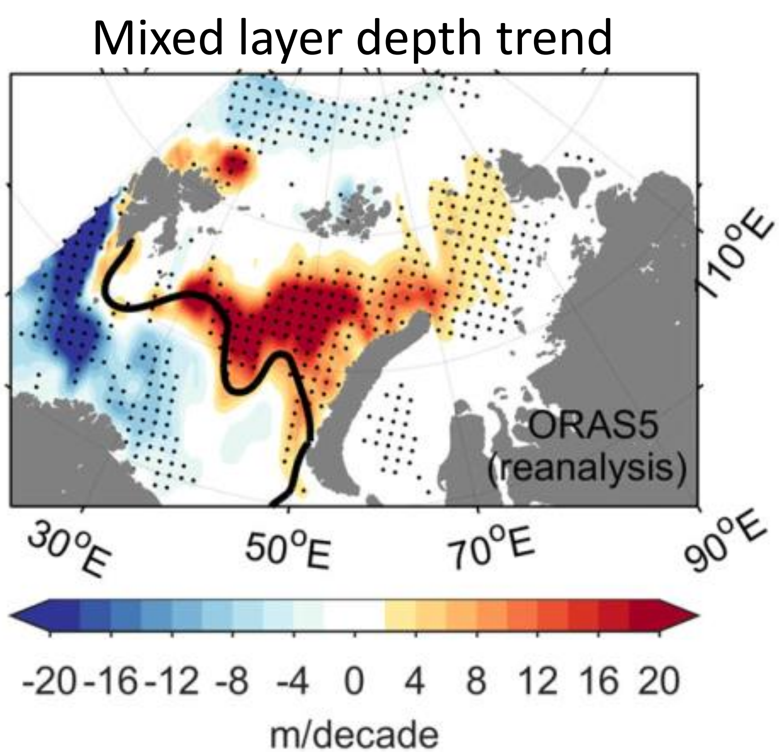
Why does surface heat flux show positive trends in ice-covered regions?

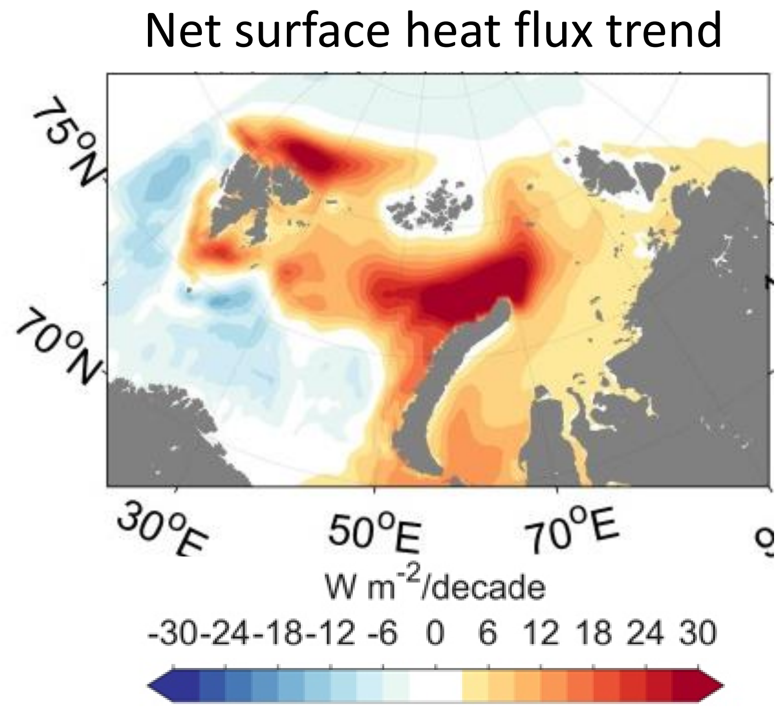




- Positive trends in ice-covered regions are mainly because sea ice decline caused by more ocean heat transport by AW inflow.
- Lower sea ice concentration results in more open water exposed to the cold air above so ocean heat (both sensible and latent heat flux) is released more efficiently.

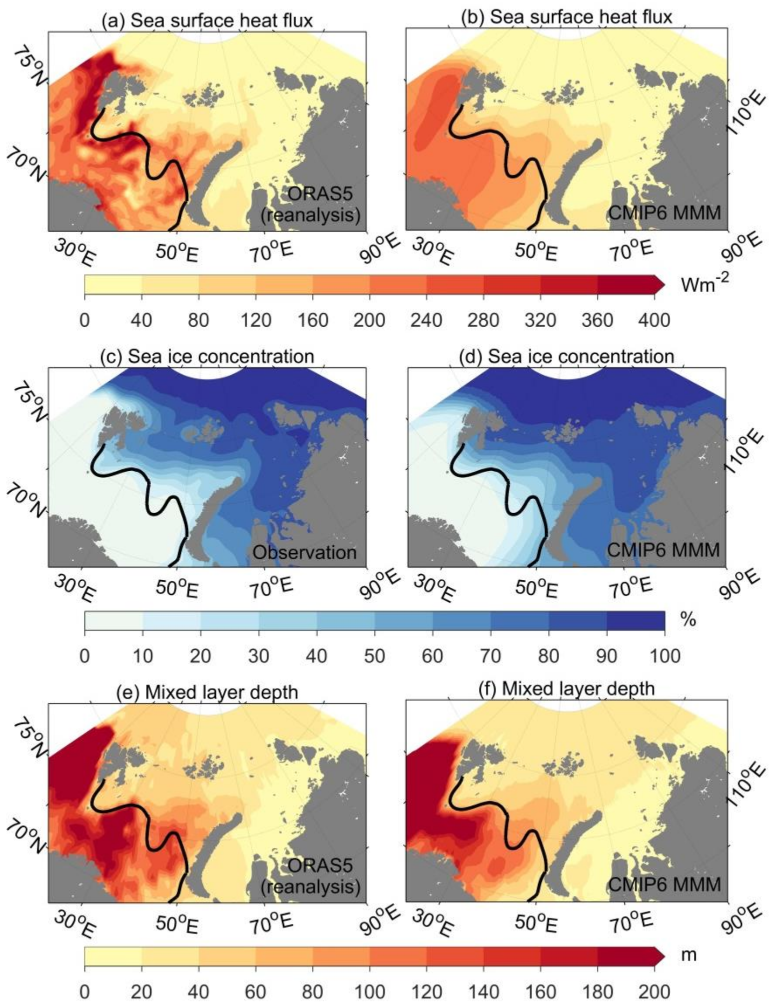
Ocean stratification



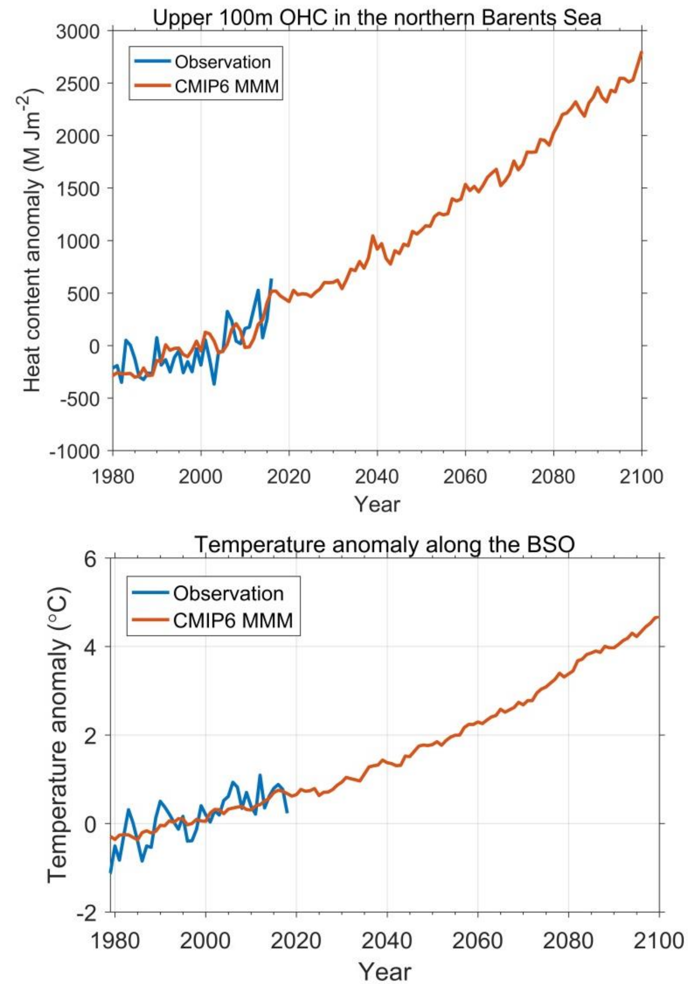


- Mixed layer depth decreases in ice-free regions and increases in ice-covered regions.
- The oceans in ice-free regions become more stable, and more heat of AW is stored in ocean and transported into ice-covered regions.
- The oceans in ice-covered regions become less stable, and more heat of AW can be transported into surface to melt sea ice.
- These changes in ocean-ice-atmosphere interaction may contribute to the poleward expansion of the Arctic Atlantification in the future.

Climate model projections based CMIP6 SSP585 scenario



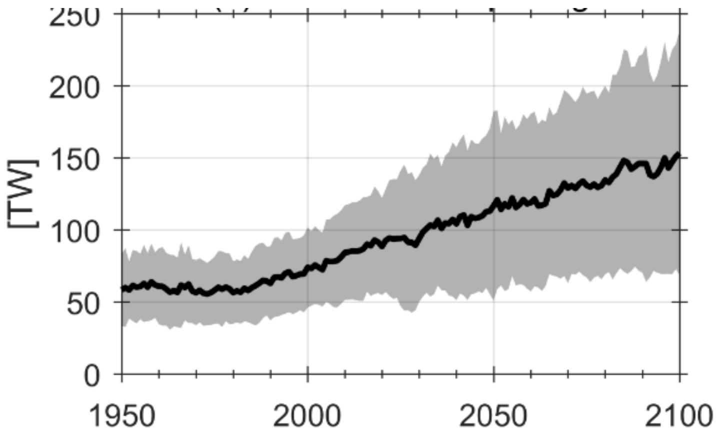
Evaluation of CMIP6 performance in simulating climatology



Evaluation of CMIP6 performance in simulating long-term trend

Climate model projections based CMIP6 SSP585 scenario

Ocean heat transport through BSO



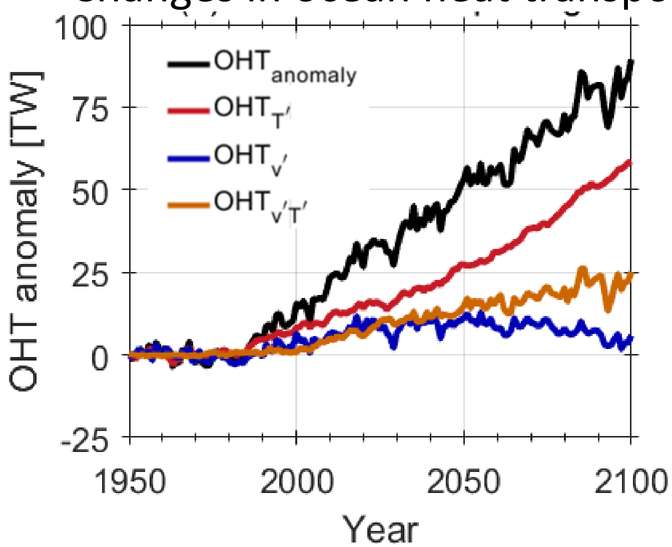
$$OHT = \rho_0 c_p \int_{-H(\lambda)}^{0} \int_{\lambda_1(z)}^{\lambda_2(z)} vT d\lambda dz$$

$$\begin{aligned} vT &= (\bar{v} + v')(\bar{T} + T') \\ &= \bar{v}\bar{T} + \bar{v}T' + v'\bar{T} + v'T' \end{aligned}$$

$$OHT = OHT_{\bar{v}\bar{T}} + OHT_{\bar{v}T'} + OHT_{v'\bar{T}} + OHT_{v'T'}$$

$$\begin{aligned} OHT_{anomaly} &= OHT - OHT_{\bar{v}\bar{T}} \\ &= OHT_{\bar{v}T'} + OHT_{v'\bar{T}} + OHT_{v'T'} \end{aligned}$$

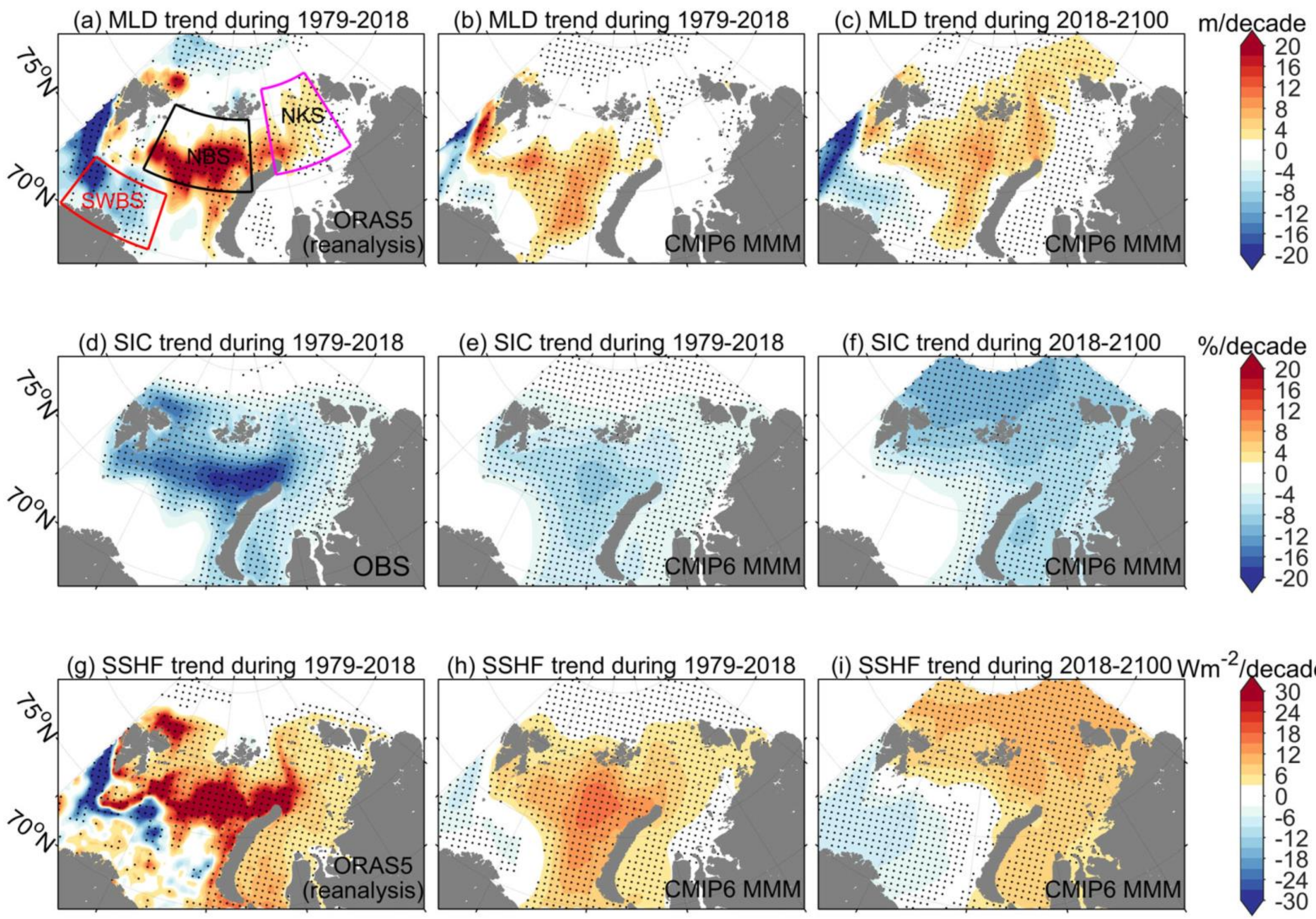
Changes in ocean heat transport



$\boldsymbol{OHT_{\bar{v}T'}}$: **temperature driven component**
$\boldsymbol{OHT_{v'\bar{T}}}$: **volume driven component**
$\boldsymbol{OHT_{v'T'}}$: **temperature and volume covariance component**

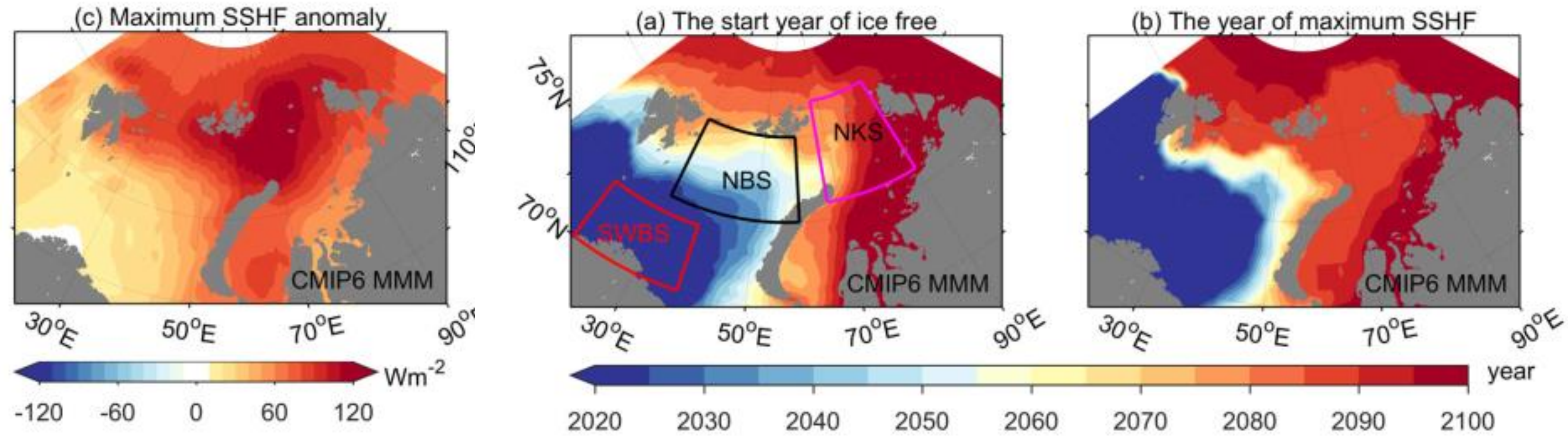
- Ocean heat transport through BSO will increase significantly in a warming climate

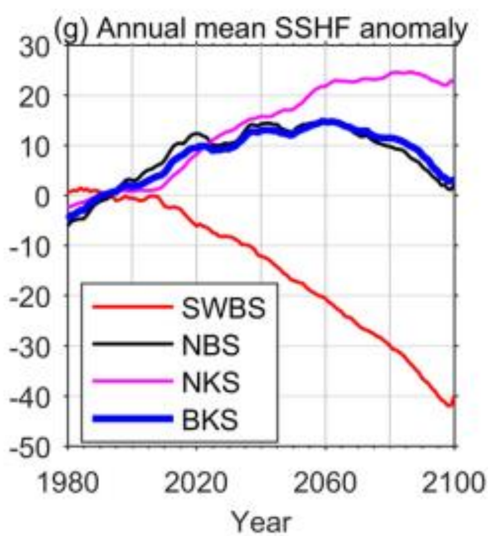
Climate model projections based CMIP6 SSP585 scenario



- CMIP6 projects the poleward expansion of the Arctic Atlantification.

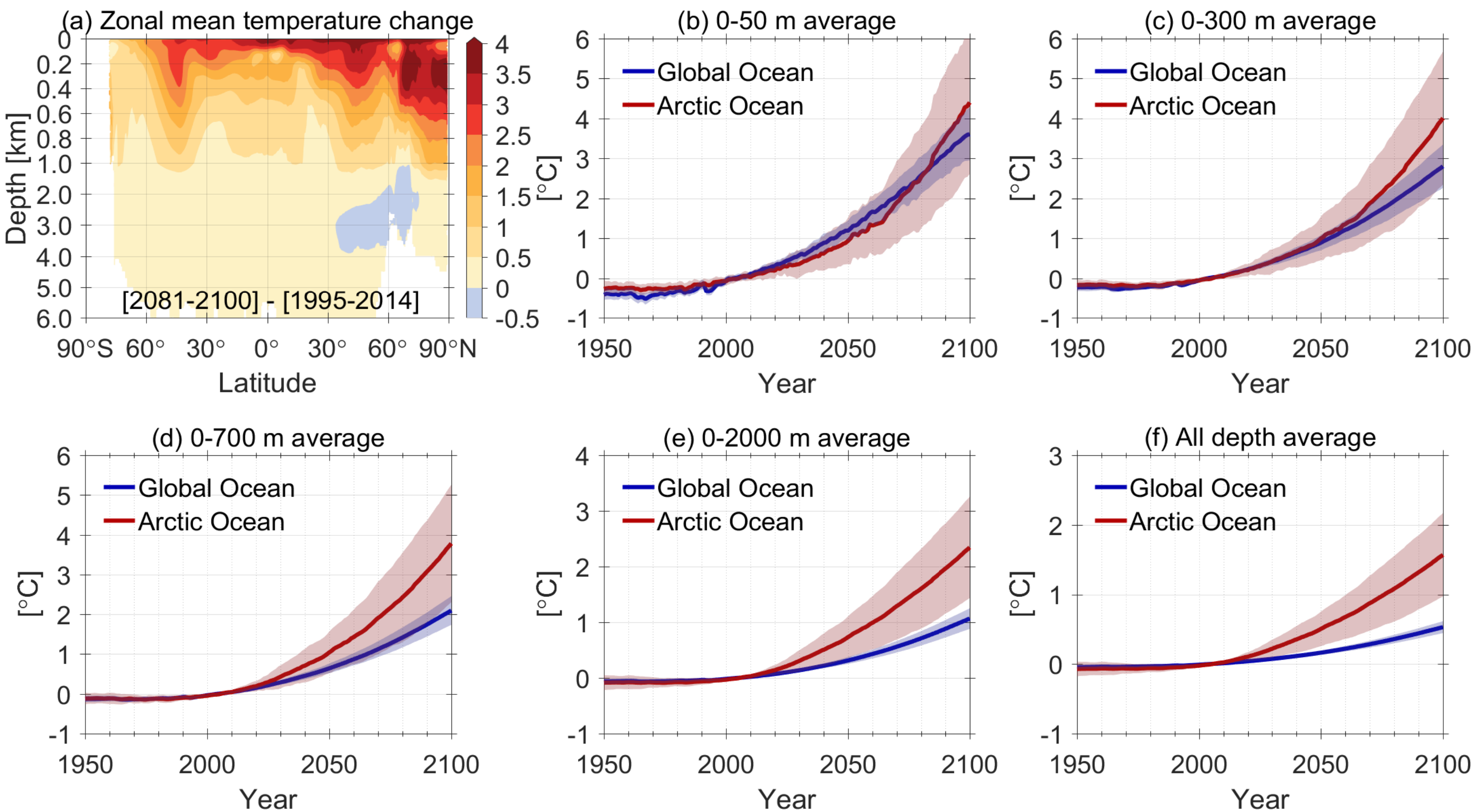
Climate model projections based CMIP6 SSP585 scenario





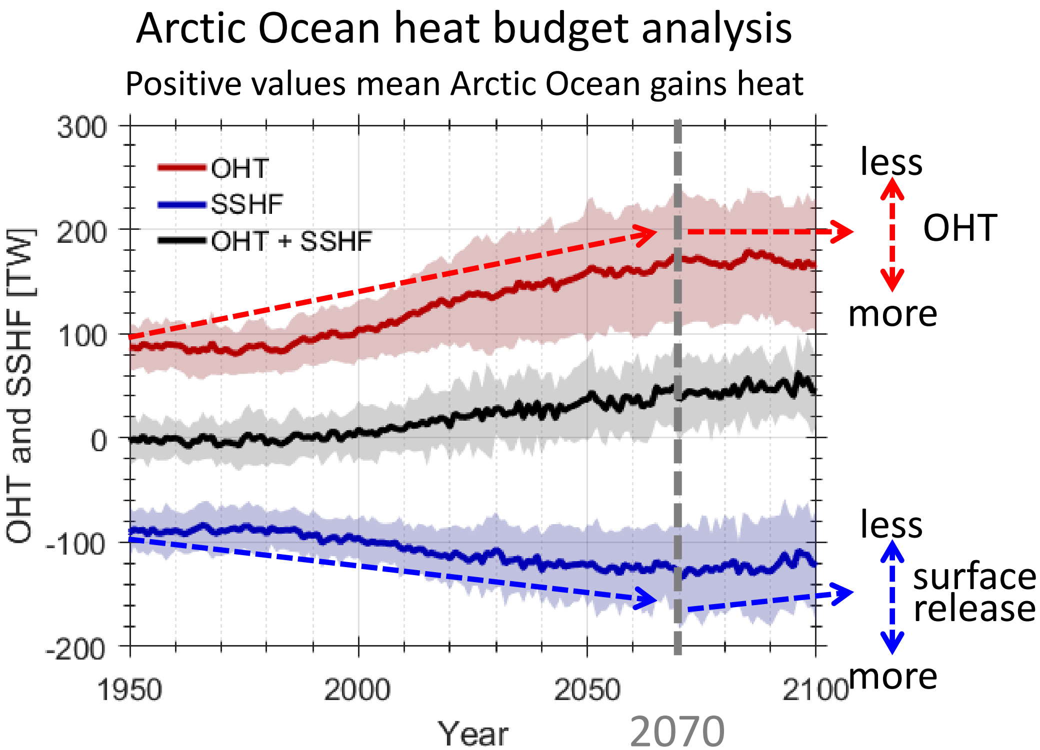
- Sea surface heat flux will have the largest anomaly in the northern Kara Sea.
- In winter, the northern Barents Sea will be ice-free and release the most heat in the 2060s, while the northern Kara Sea will become ice-free and release the most heat in the 2080s .

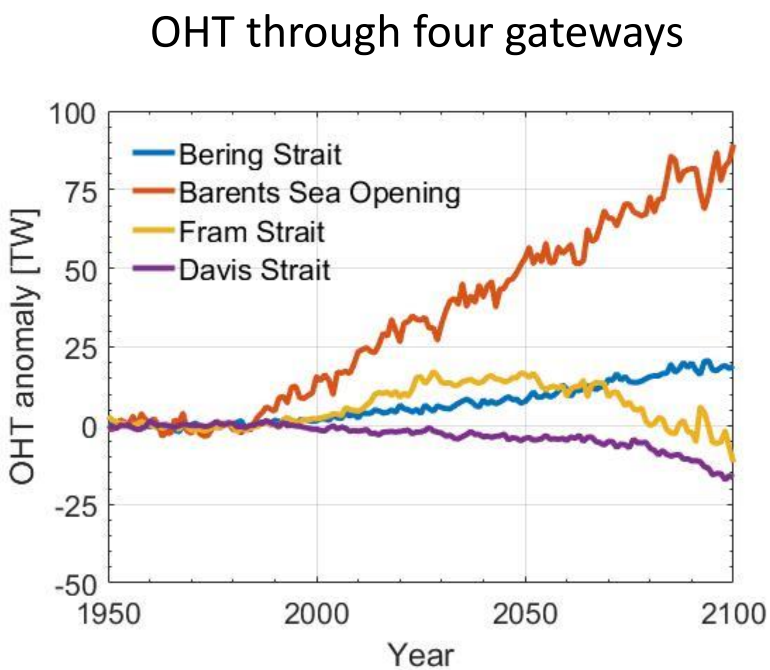
The roles of ocean-ice-atmosphere interaction in Arctic Ocean warming



Arctic Ocean will warm much faster than the average global ocean.

The roles of ocean-ice-atmosphere interaction in Arctic Ocean warming

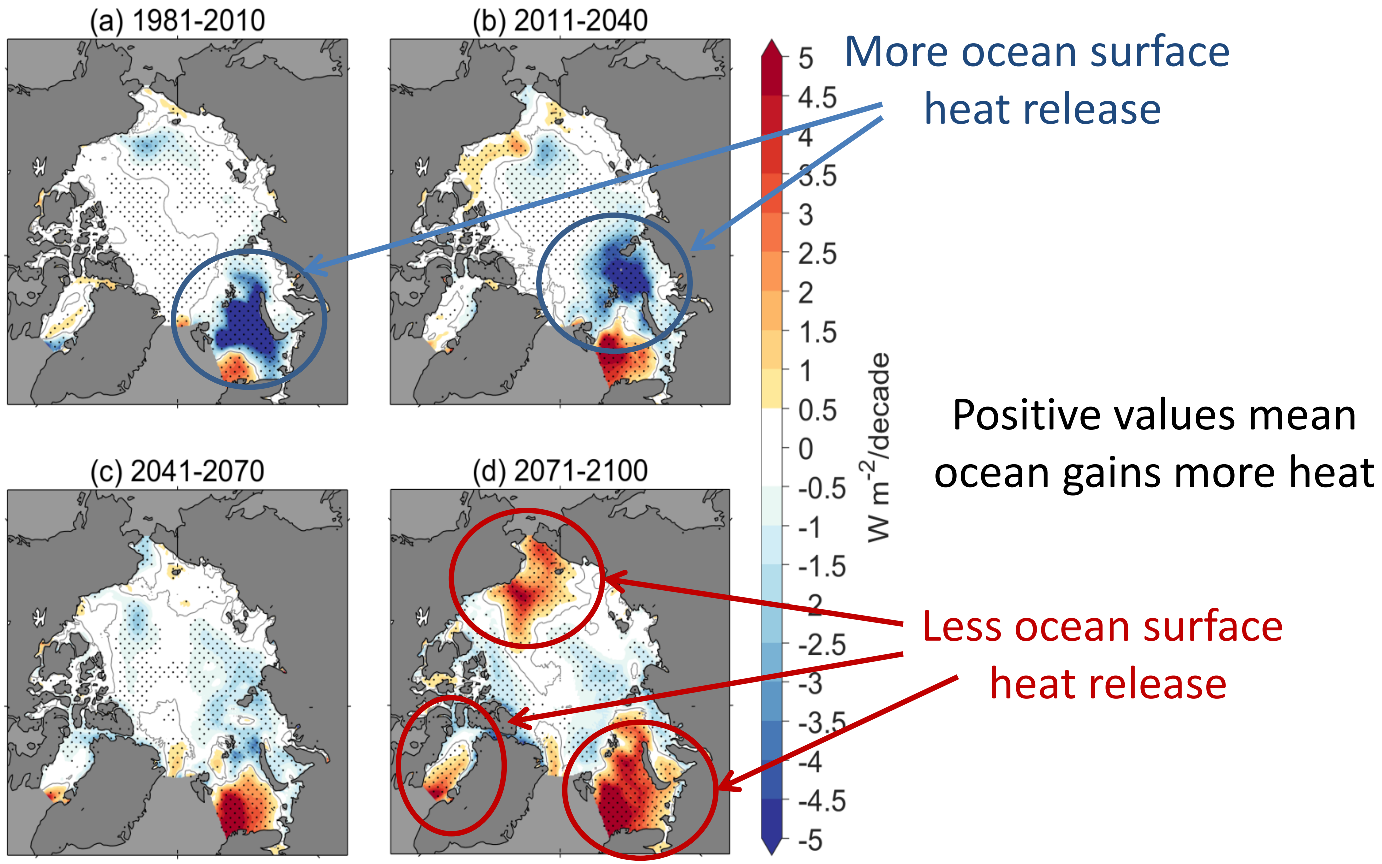




- Before 2070, Arctic Ocean warming is mainly caused by enhanced poleward ocean heat transport.
- After 2070, Arctic Ocean warming is mainly caused by less ocean heat release in the Arctic Ocean.

The roles of ocean-ice-atmosphere interaction in Arctic Ocean warming

Linear trends of annual mean sea surface heat flux in the Arctic Ocean for different periods



- Arctic Ocean warming during 2071–2100 is mainly caused by less ocean heat release in the Barents Sea, Kara Sea, Chukchi Sea and Baffin Bay .

Conclusions

- In ice-free regions (the southwestern Barents Sea), ocean surface heat flux has negative trends over the past four decades, while in ice-covered regions (the northern Barents and Kara Seas) it has positive trends.
- Negative trends in ice-free regions are mainly because the near-surface air has a stronger warming trend than the ocean, and positive trends in ice-covered regions are mainly because significant sea ice decline caused by more ocean heat transport by AW inflow.
- Mixed layer depth also decreases in ice-free regions and increases in ice-covered regions.
- These changes in ocean-ice-atmosphere interaction will contribute to the poleward expansion of the Arctic Atlantification.
- Under scenario SSP585, before 2070, Arctic Ocean warming is mainly caused by enhanced poleward ocean heat transport, while after 2070, Arctic Ocean warming is mainly caused by ocean-ice-atmosphere interaction in both Atlantification and Pacification.

Shu, Q., Wang, Q., Song, Z., & Qiao, F. (2021). The poleward enhanced Arctic Ocean cooling machine in a warming climate. *Nature communications*, *12*(1), 1-9. https://doi.org/10.1038/s41467-021-23321-7