High-Resolution Climate Model Projections of Beaufort Gyre Freshwater and AMOC Decline

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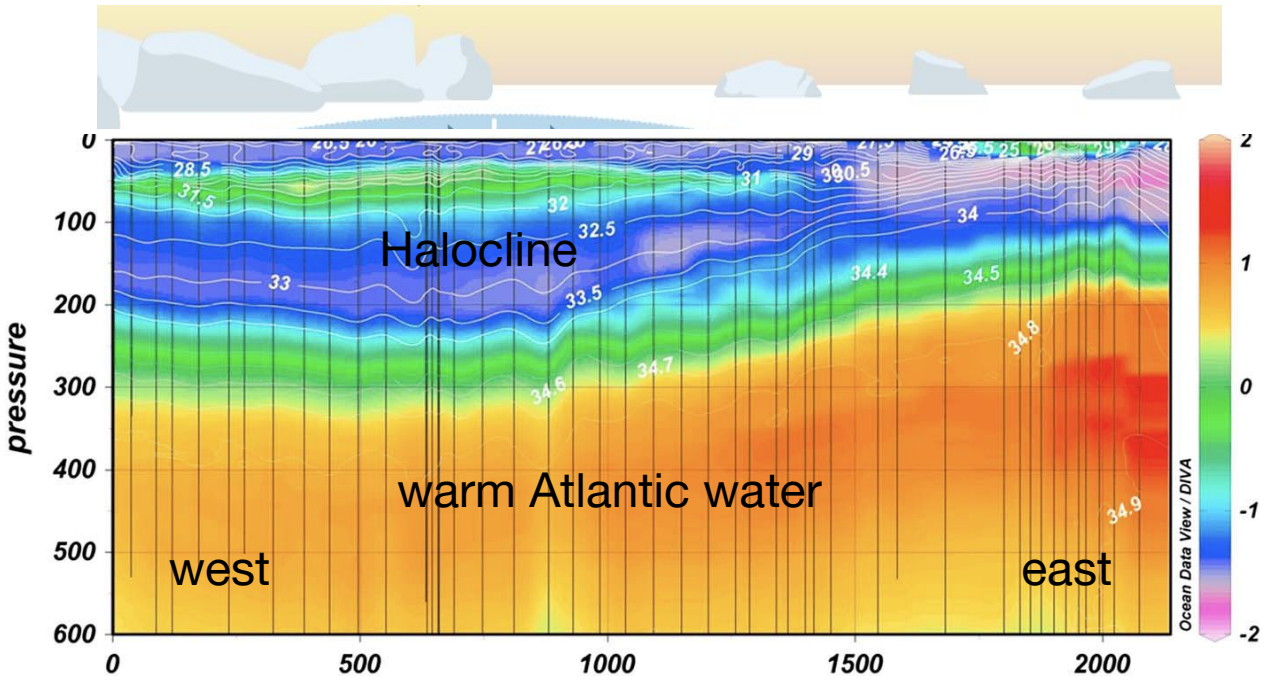
WOODS HOLE OCEANOGRAPHIC INSTITUTION

Freshwater (FW) is Important for High-latitude Oceans

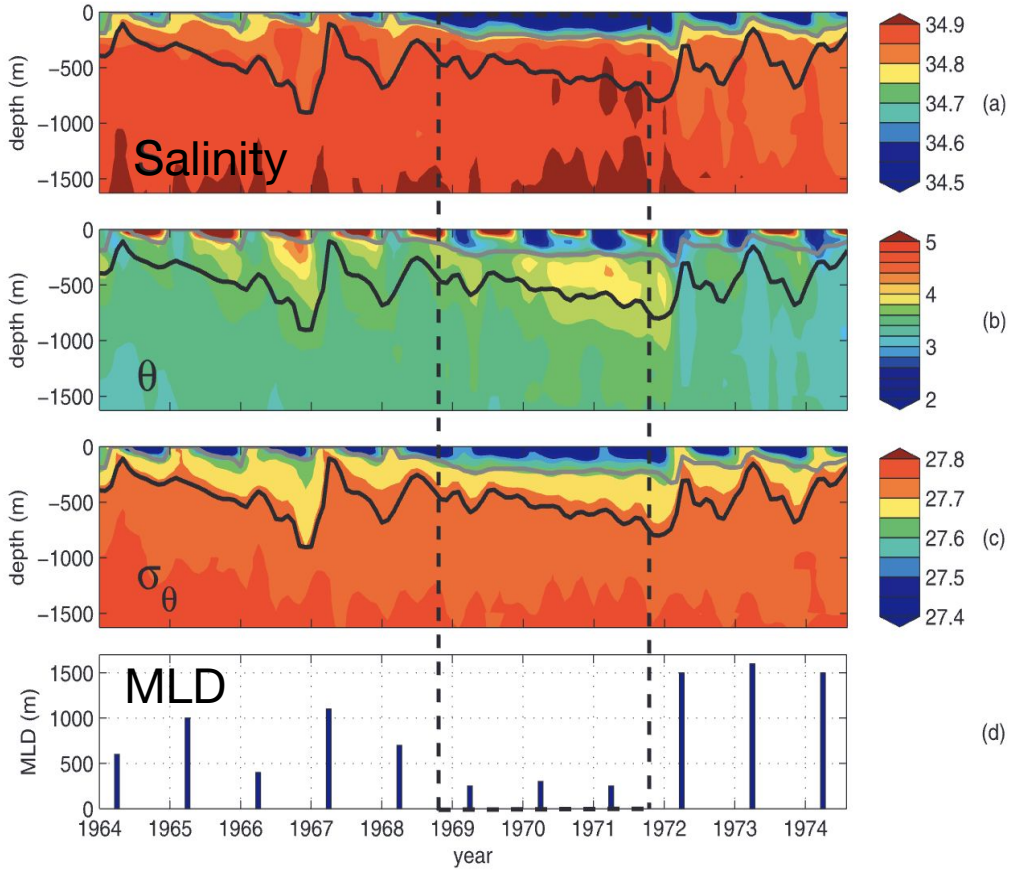
salinity → density → vertical stratification

restrict Arctic heat and nutrient uptake



Carmack et al. (2016)

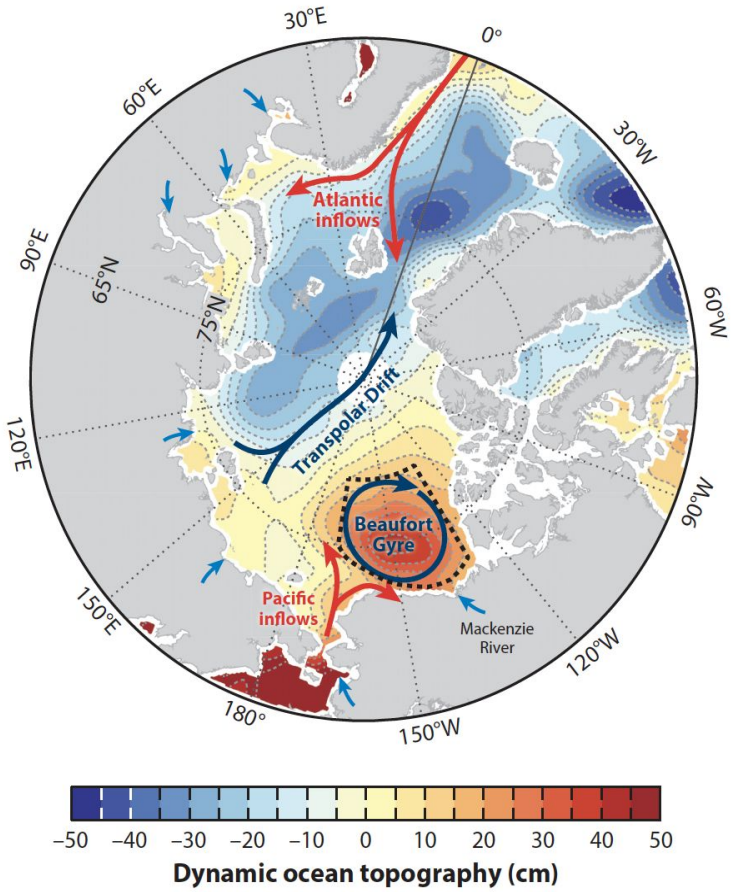
suppress Labrador Sea deep convection



Gelderloos et al. (2012)

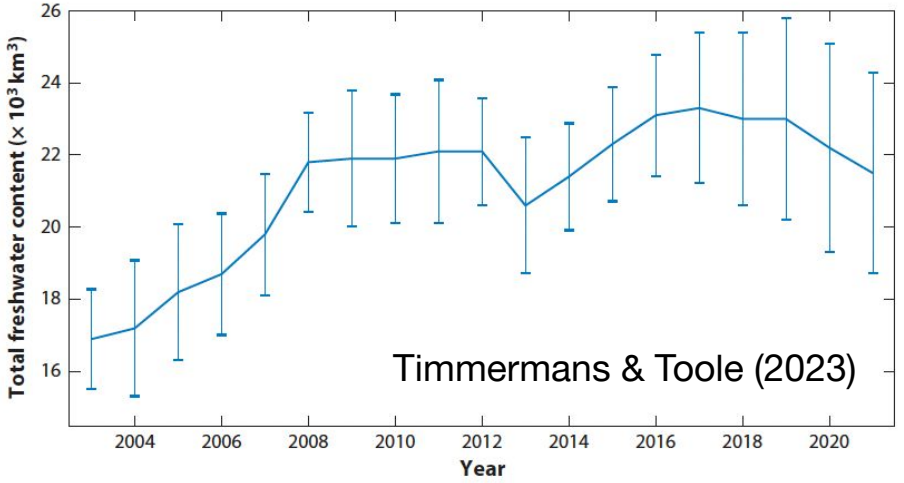
Past and Future Changes of the Arctic Beaufort Gyre

wind-driven liquid FW reservoir

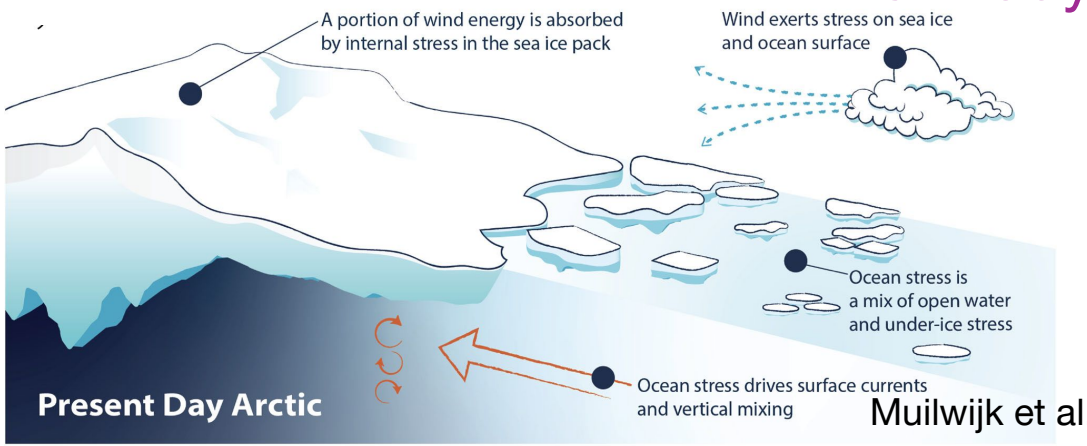


Timmermans & Toole (2023)

precursor to huge FW release



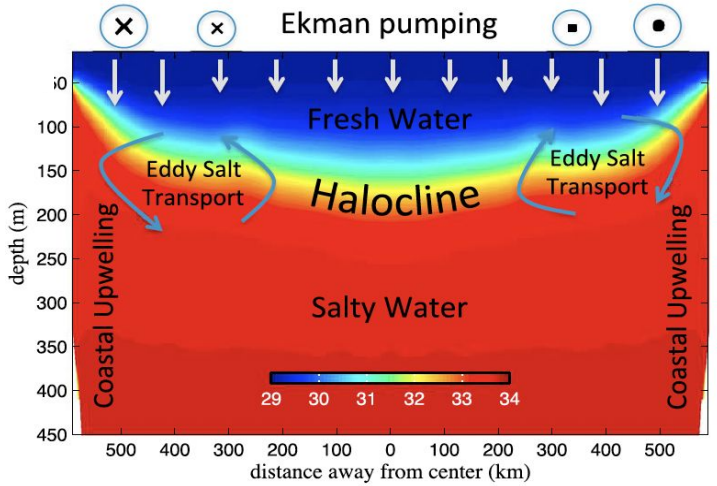
importance of sea ice
- dynamic
- thermodynamic



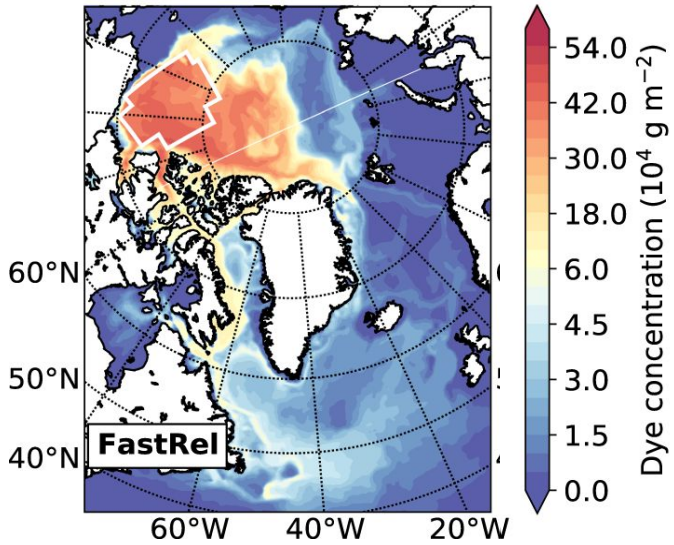
Muilwijk et al. (2024)

Resolving Unresolved: A High-Resolution Simulation

unresolved FW processes



Manucharyan and Spall (2015)



Zhang et al. (2021)

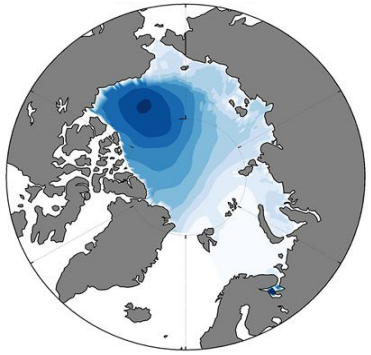
high-resolution simulation: CESM1-HR

- ✔ ocean and sea ice ~0.1°
  ~5km (7km) in the Arctic (subarctic)
- ✔ atmosphere~0.25°
- ✔ under CMIP5 experiment protocol
  500-year preindustrial control
  1850-2005 with historical forcing
  2006-2100 with RCP8.5 forcing

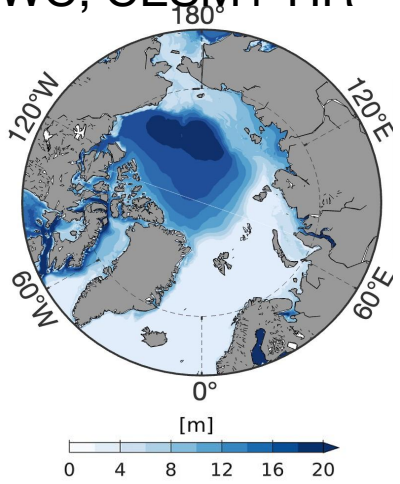
Simulation and Prediction of Beaufort Gyre in CESM1-HR

well-represented liquid freshwater content (LFWC) and sea ice condition

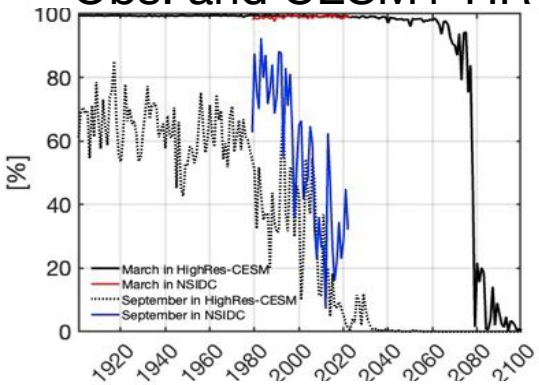
LFWC, Obs.



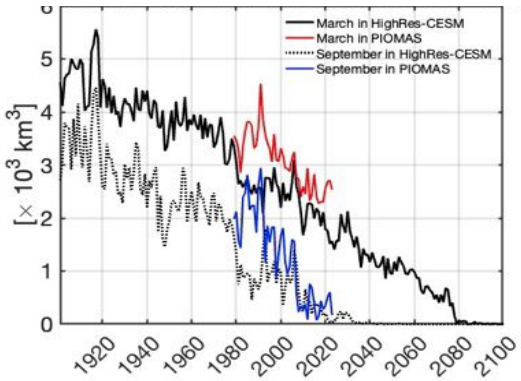
LFWC, CESM1-HR



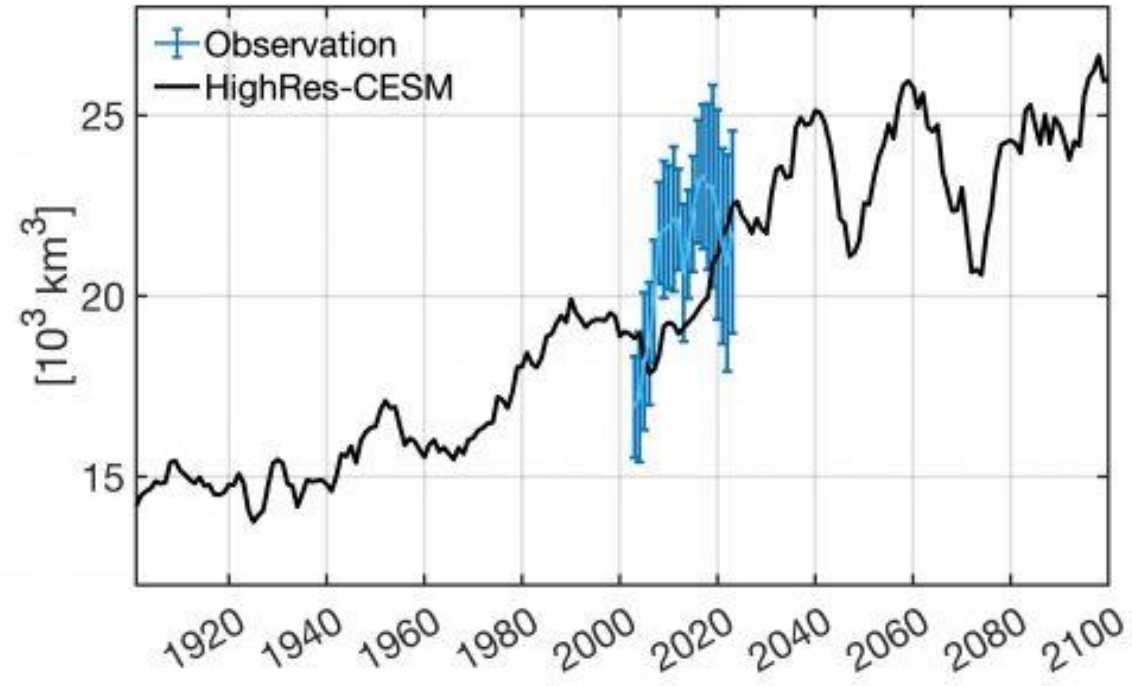
Sea ice concentration in Obs. and CESM1-HR



Sea ice volume in Obs. and CESM1-HR



Predicted increase of LFWC and its variability



Shan, X., Spall, M., Sun, S., & Wu, L. (2025). Beaufort Gyre liquid freshwater content change under greenhouse warming from an eddy‐resolving climate simulation. Geophysical Research Letters, 52, e2024GL113847.* https://doi.org/10.1029/2024GL113847

Sea Ice Strongly Affects the LFWC Responses

$$\underbrace{\frac{\partial \mathrm{LFWC}}{\partial t}}_{F_{\mathrm{tend}}} = \underbrace{-\iiint \nabla_h \cdot \left[\mathbf{u}_h \left(\frac{S_{\mathrm{ref}} - S}{S_{\mathrm{ref}}}\right)\right] dV}_{F_{\mathrm{hori}}} \underbrace{- \iint \frac{d\eta}{dt}\left(\frac{S_{\mathrm{ref}} - S}{S_{\mathrm{ref}}}\right) dxdy}_{F_{\mathrm{ssh}}} \underbrace{+ \iint w\left(\frac{S_{\mathrm{ref}} - S}{S_{\mathrm{ref}}}\right) dxdy\Big|_{z=z_b}}_{F_{\mathrm{bot}}} + F_{\mathrm{surf}} + F_{\mathrm{turb}}$$

[1] 1960-2030: strong LFWC increase

- Sea ice melt adds liquid freshwater to the gyre, most of which remains

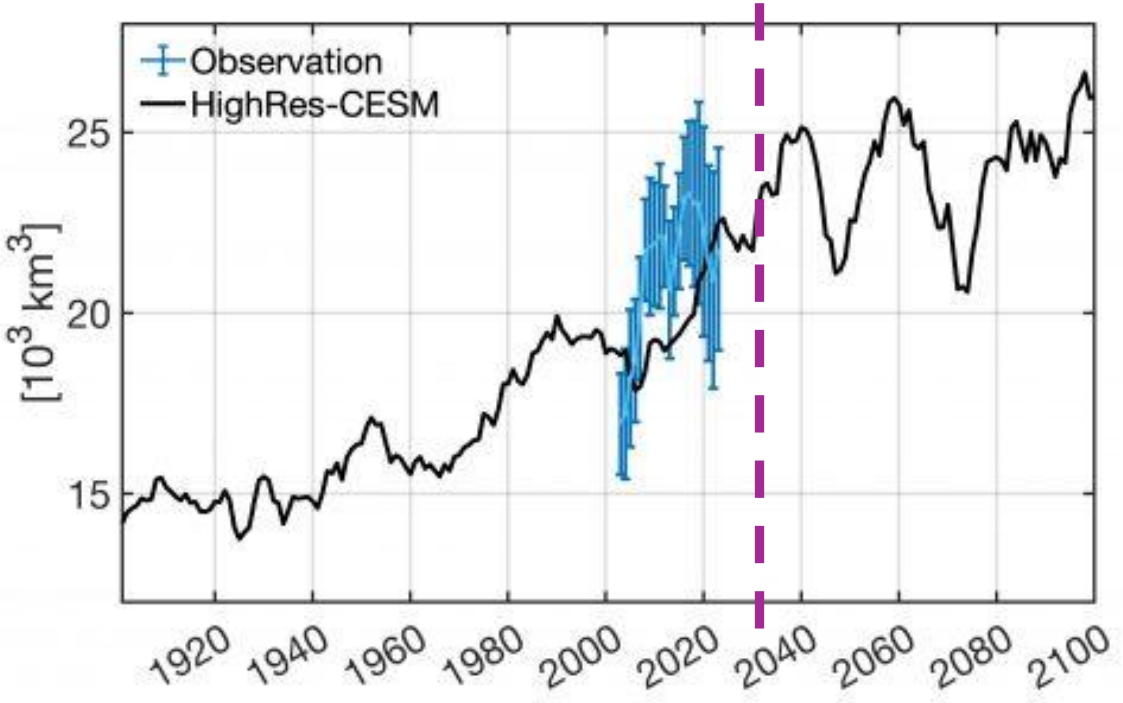
[2] 2030-2100: weak LFWC increase

- Stronger sea surface curl (SSC) brings more freshwater into the gyre, but much of it is removed by eddy advection
- Weaker wind stress curl (WSC), but more efficient air-sea momentum transfer under reduced sea ice

[3] 2030-2100: strong LFWC variability

- SSC variability is the main contributor
- Stronger WSC variability and more efficient air-sea momentum transfer

FW budget varies over time



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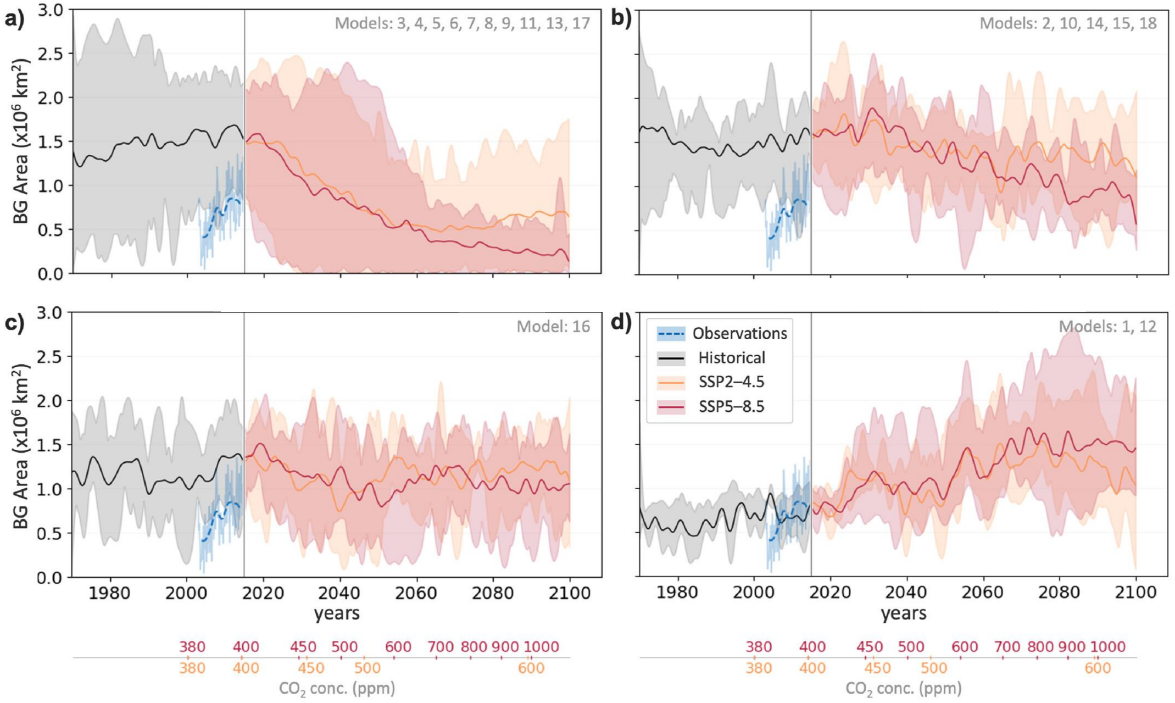
Uncertain Fate of the Beaufort Gyre

Will the gyre strengthen or weaken in the future?

10 disappearing, CMIP6 5 decreasing, CMIP6

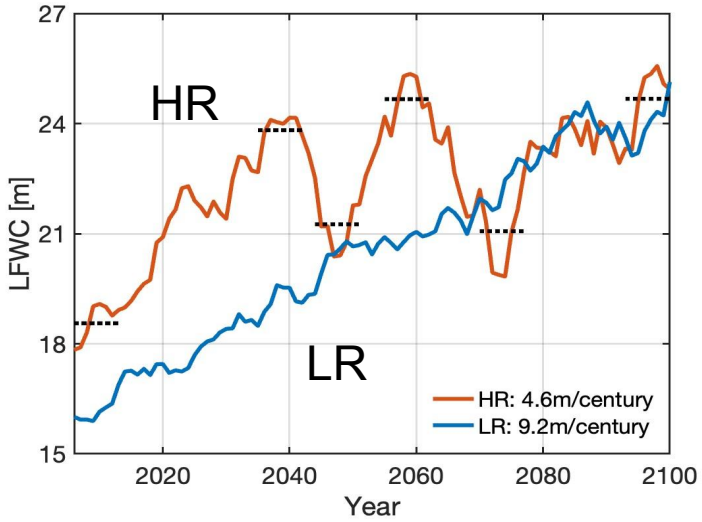


1. ACCESS-CM2
2. AWI-CM-1-1-MR
3. CanESM5
4. CMCC-ESM2
5. CNRM-CM6-1
6. CNRM-CM6-1-HR
7. EC-Earth3
8. EC-Earth3-Veg
9. EC-Earth3-Veg-LR
10 .GFDL-ESM4
11. HadGEM3-GC31-LL
12. INM-CM5-0
13. IPSL-CM6A-LR
14. MIROC6
15. MPI-ESM1-2-HR
16. MPI-ESM1-2-LR
17. MRI-ESM2-0
18. NorESM2-LM

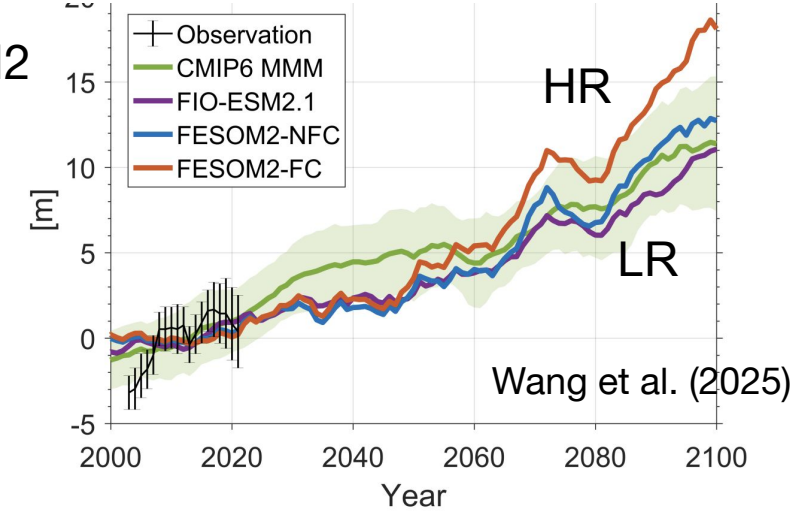
Athanase et al. (2025)

How much will it fluctuate? Will high-resolution increase its variability?

CESM1



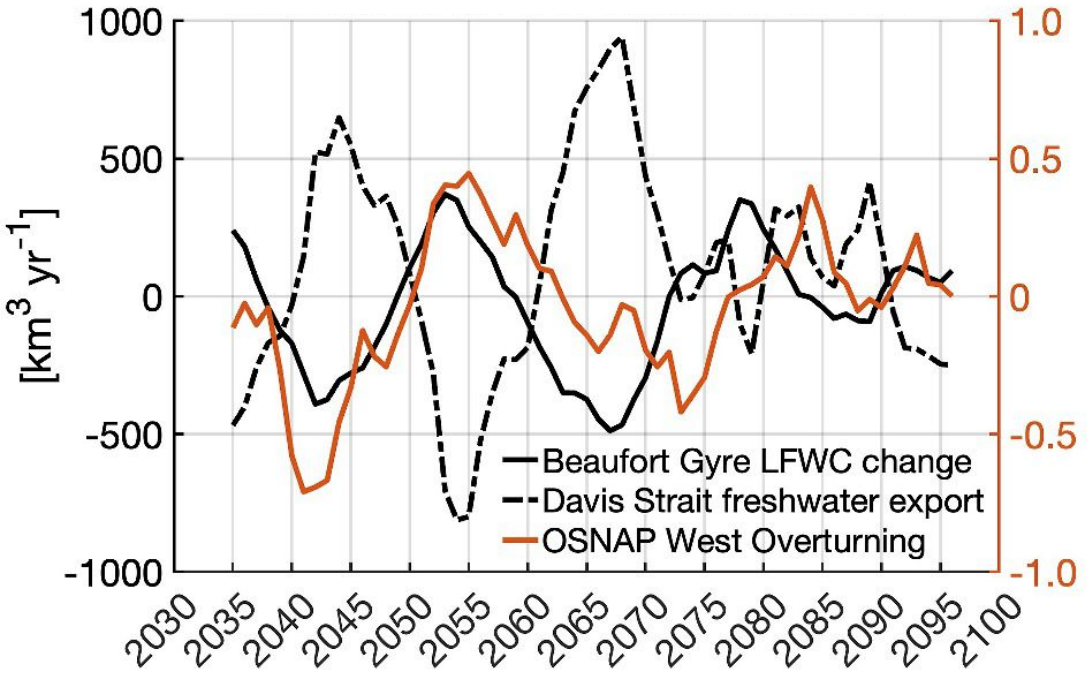
FESOM2



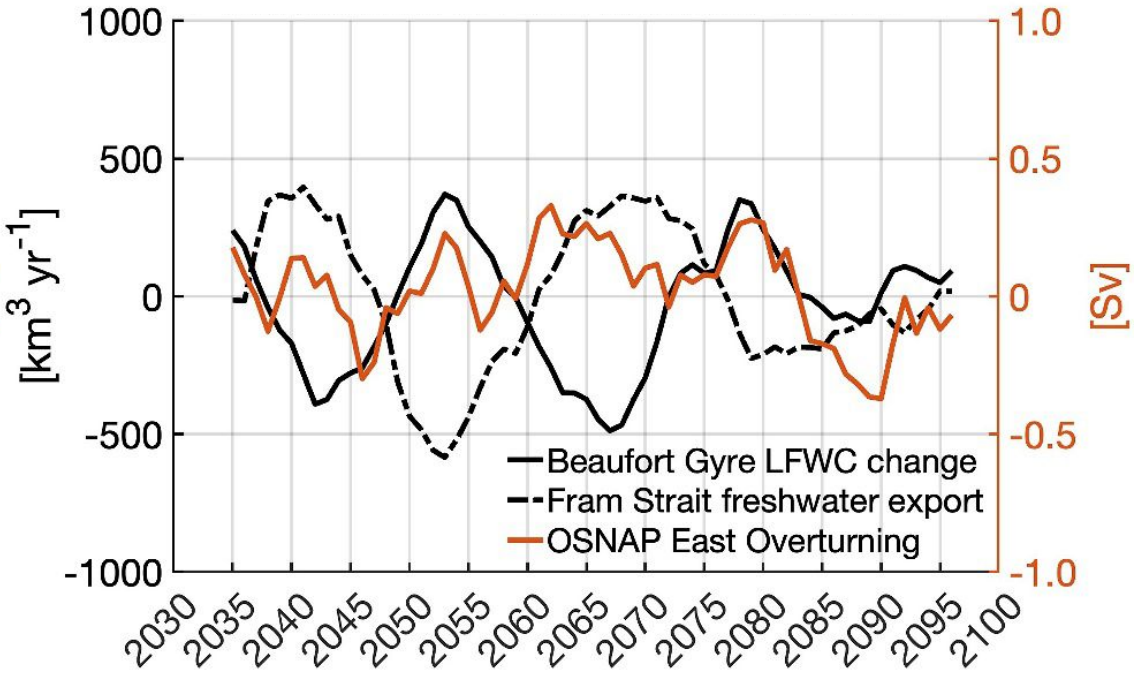
Downstream Impacts of Beaufort Gyre LFWC Oscillation

- regulate Arctic freshwater exports
- coincident with an O (0.5 Sv) change in Labrador overturning (~10% compared to the simulated climatology)

Davis Strait FW export and OSNAP-West overturning



Fram Strait FW export and OSNAP-East overturning



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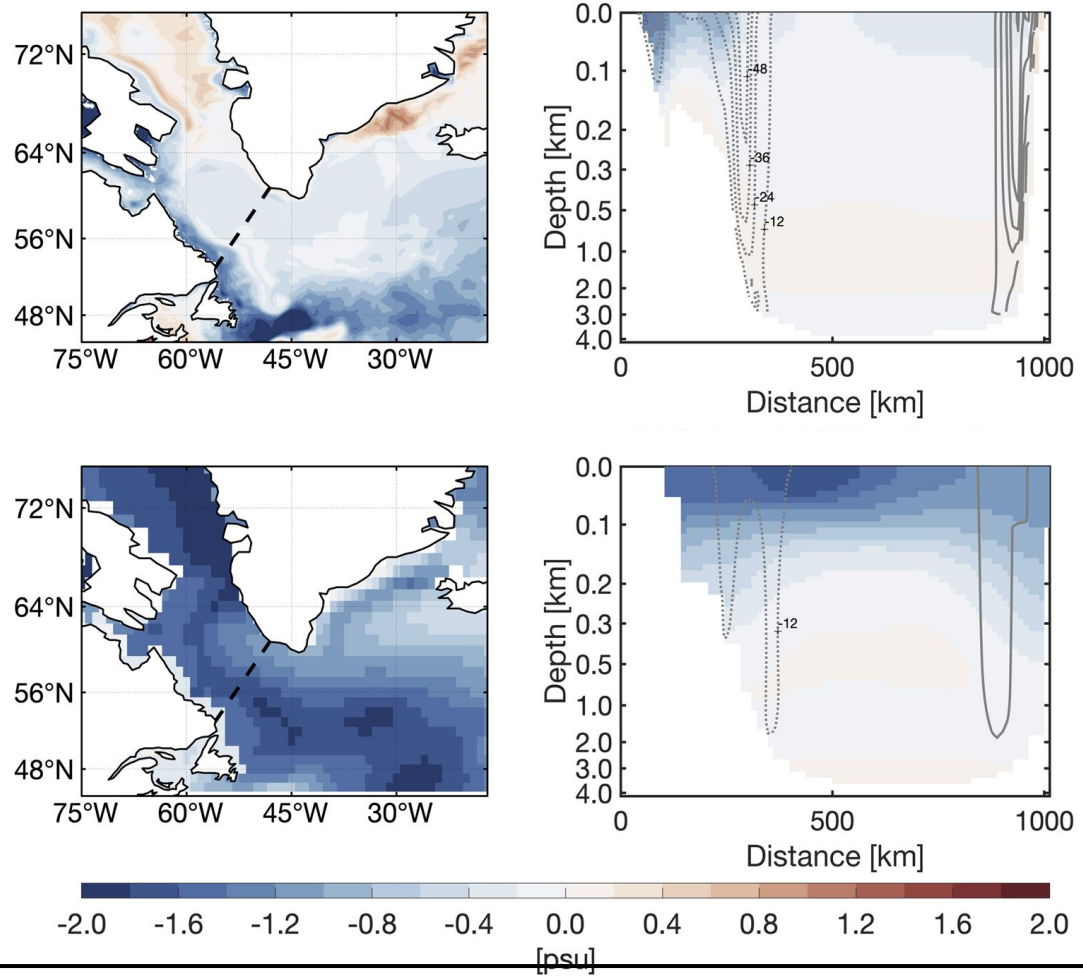
Resolution Matters after Freshwater Leaving the Arctic

FW confined on the boundary in CESM1-HR while spread into basin interior in CESM1-LR

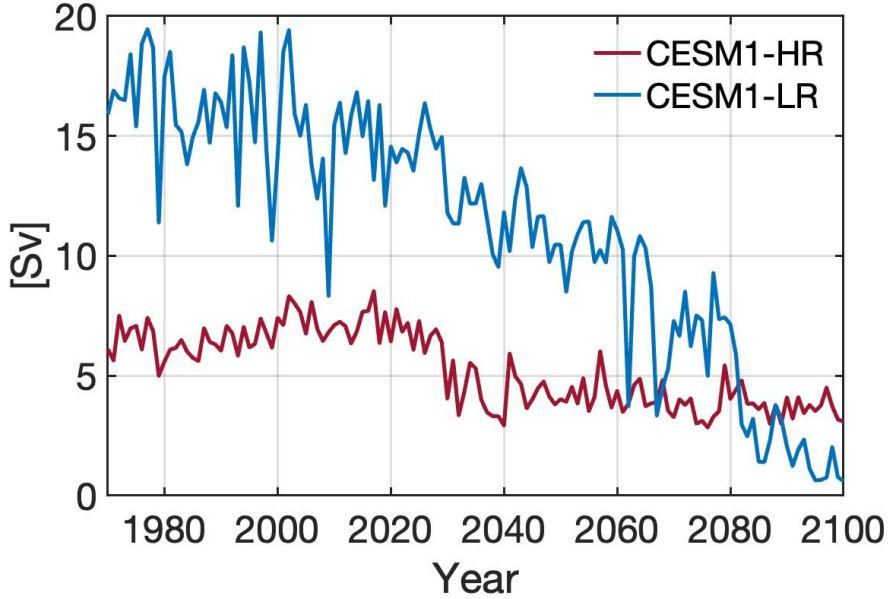
Future salinity change and simulated boundary current

CESM1 -HR

CESM1 -LR



Labrador overturning shutdown in CESM1-LR



Shan, X., Sun, S., Wu, L., & Spall, M. (2024). Role of the Labrador current in the Atlantic meridional overturning circulation response to greenhouse warming. Nature Communications, 15(1), 7361. https://doi.org/10.1038/s41467-024-51449-9

Summary

- High-resolution prediction of future Beaufort Gyre liquid freshwater content (LFWC)
  - Beaufort Gyre LFWC and its decadal variability increase under greenhouse warming in a high-resolution CESM simulation
  - Sea ice strongly affects the LFWC changes through both thermodynamic (phase transition) and dynamic processes (momentum filter, the surface forcing change does NOT follow the wind forcing change)
  - Decadal oscillation of the LFWC regulates Arctic freshwater exports with some influence on the subarctic overturning

- Resolution-dependent freshwater distribution in the subarctic region
  - In the high-resolution CESM, freshwater is confined to the boundary region by a better-simulated Labrador Current, whereas in the low-resolution CESM, it spreads excessively into the basin interior.
  - The Labrador overturning is completely shut down due to underrepresented boundary currents, leading to a stronger AMOC decline in low-resolution models.

Shan*, X., Spall, M., Sun, S., & Wu, L. (2025). Beaufort Gyre liquid freshwater content change under greenhouse warming from an eddy‐resolving climate simulation. Geophysical Research Letters, 52, e2024GL113847. https://doi.org/10.1029/2024GL113847

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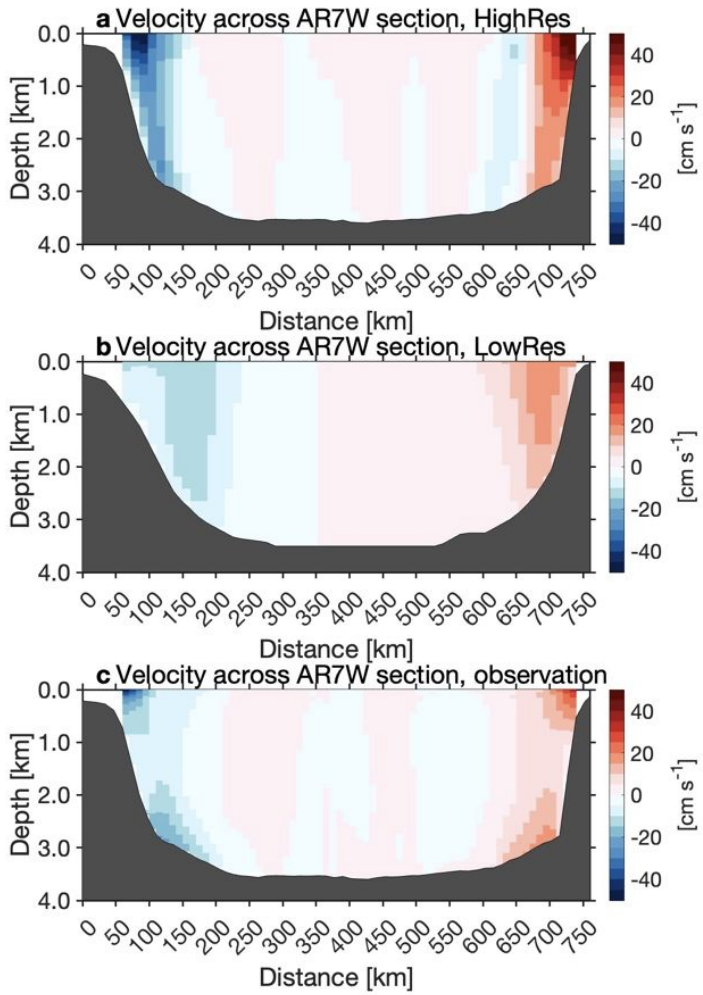
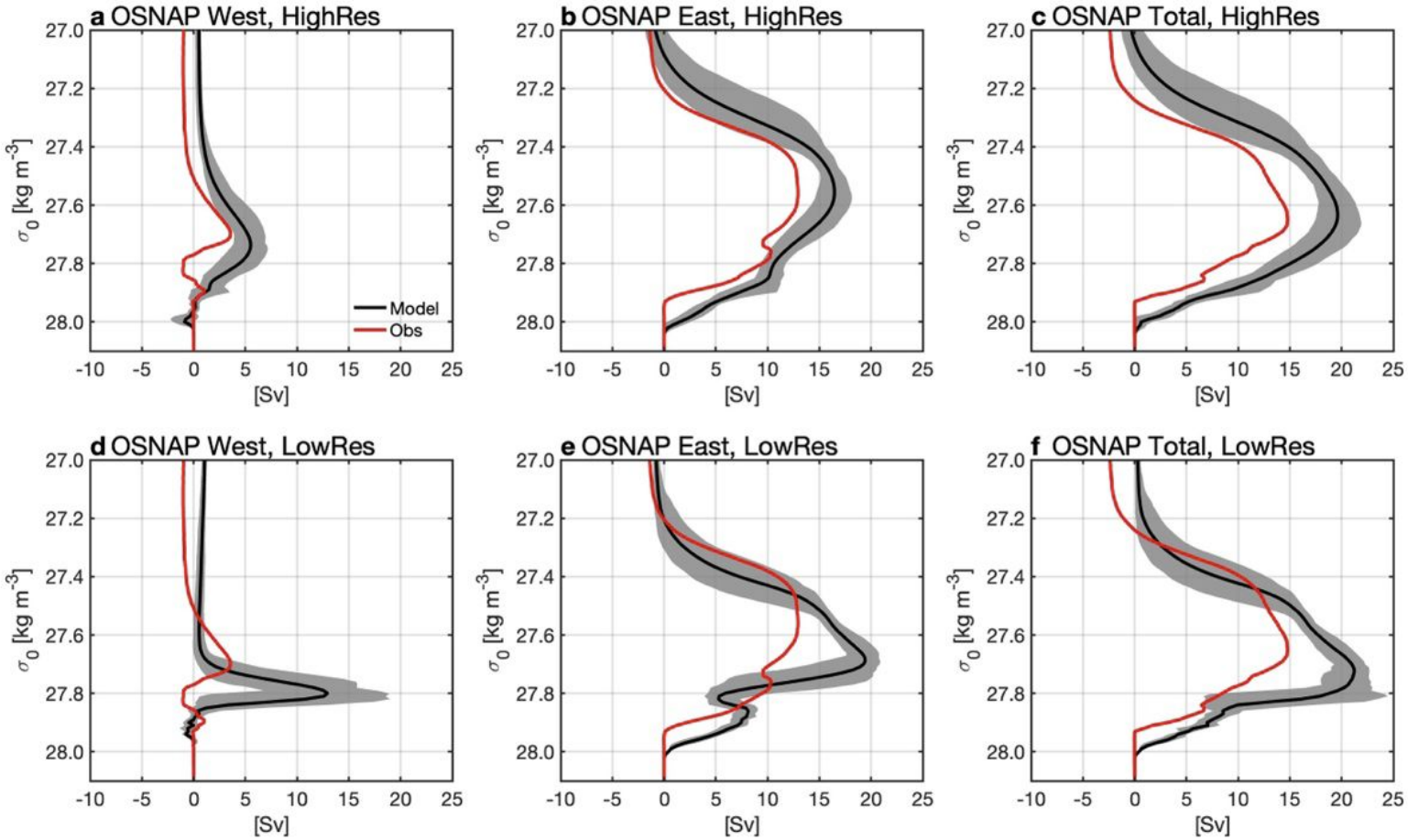
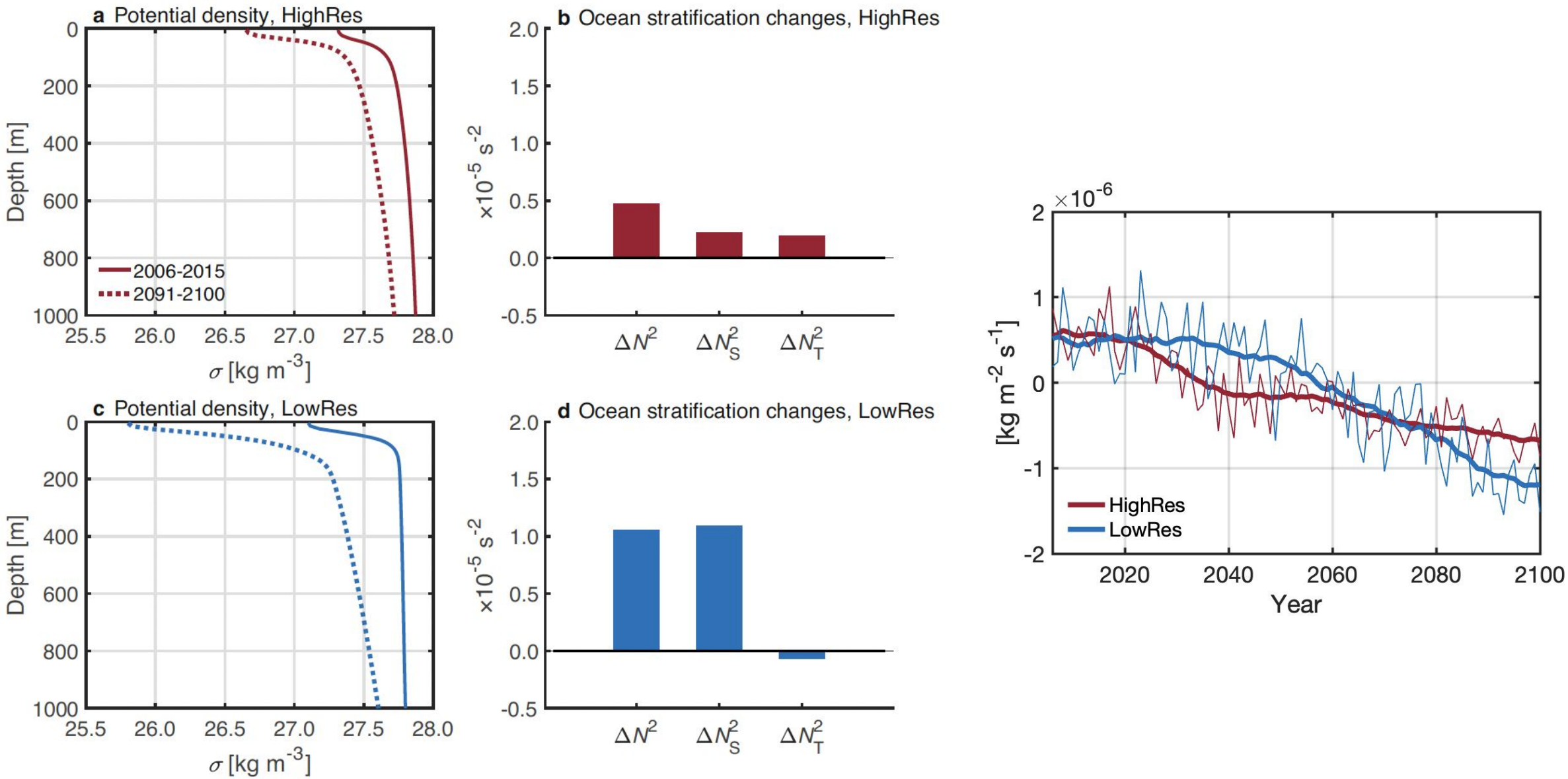
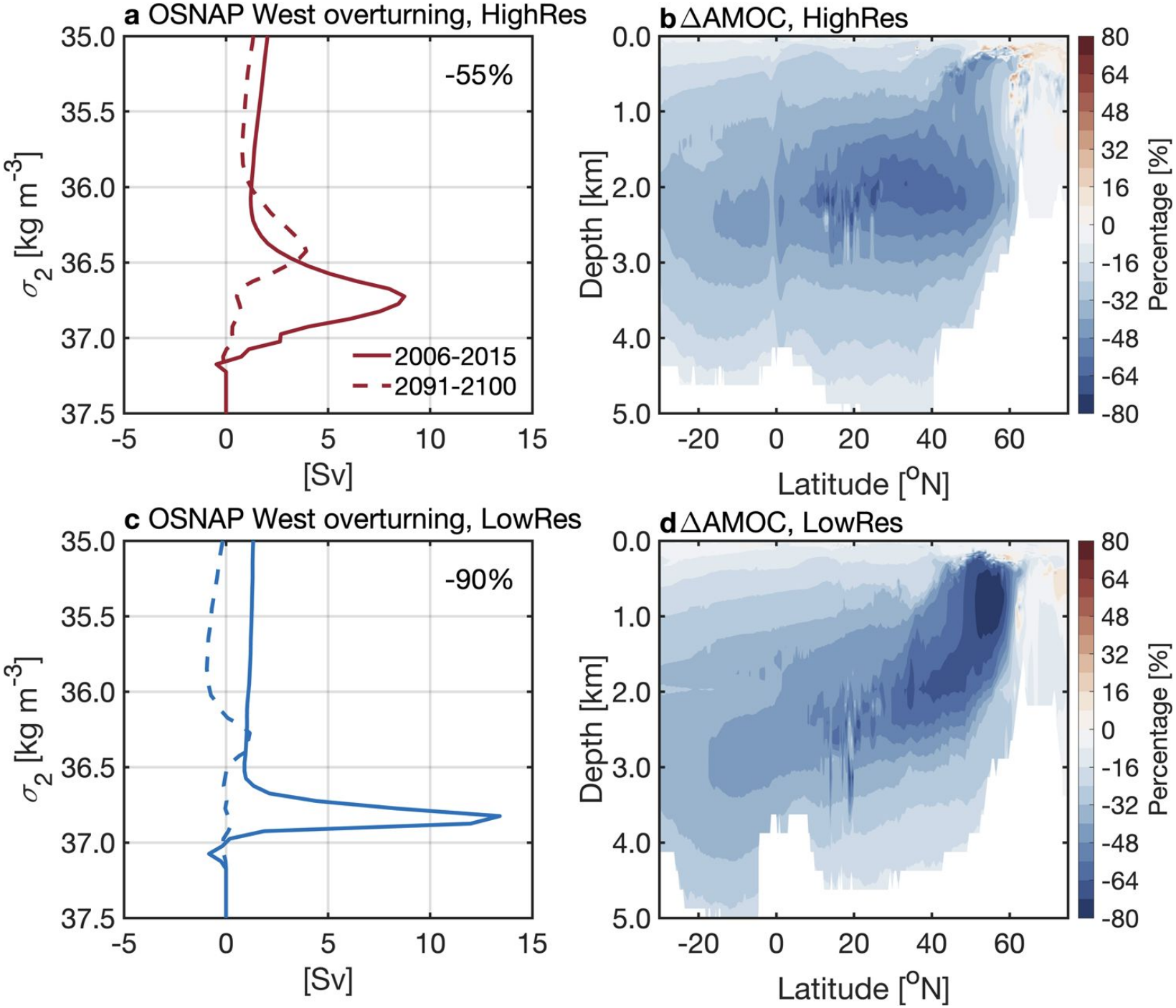
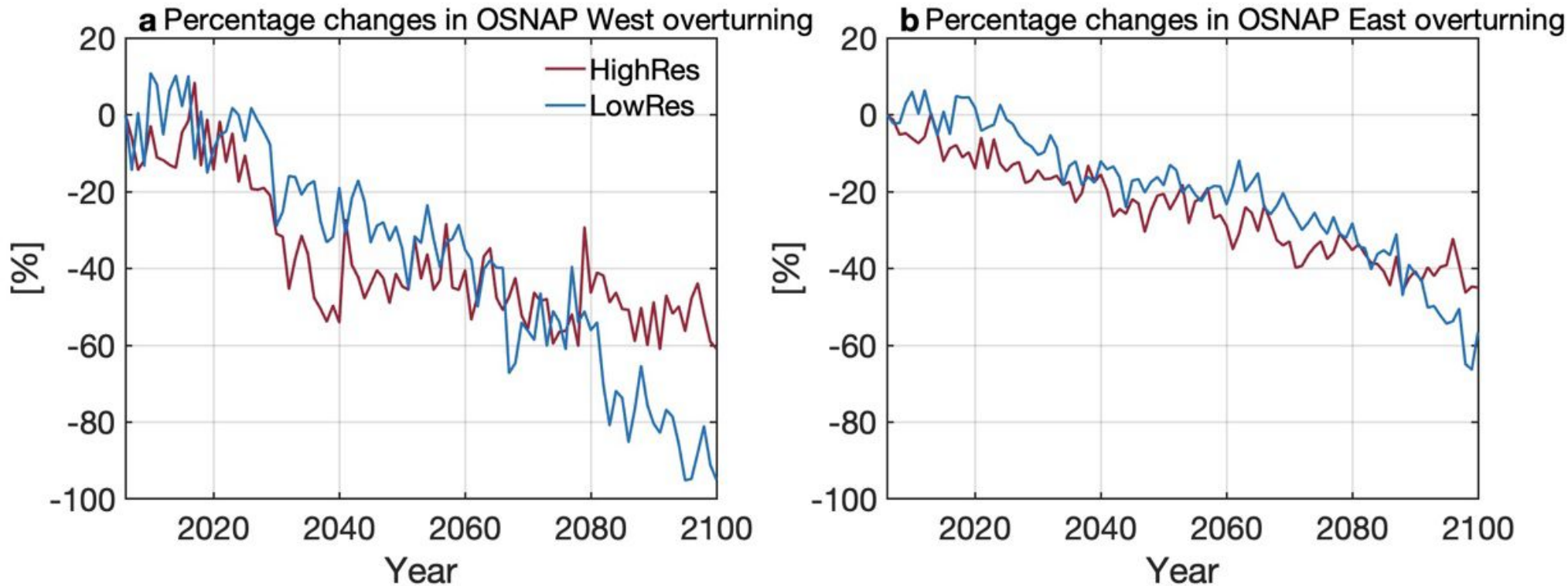
extra slides

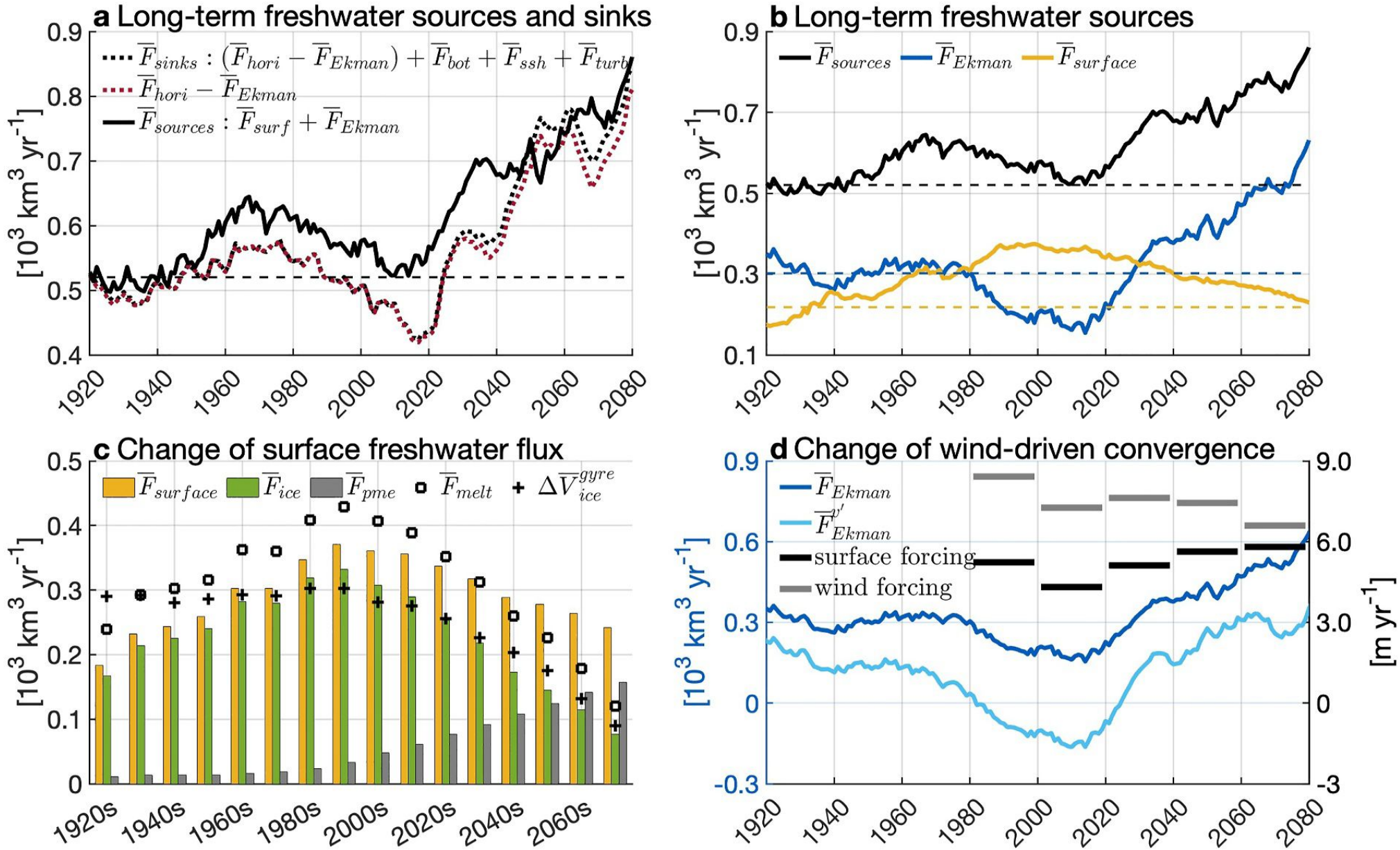

a Velocity across AR7W section, HighRes
b Velocity across AR7W section, LowRes
c Velocity across AR7W section, observation
Depth [km]
Distance [km]
[cm s^{-1}]

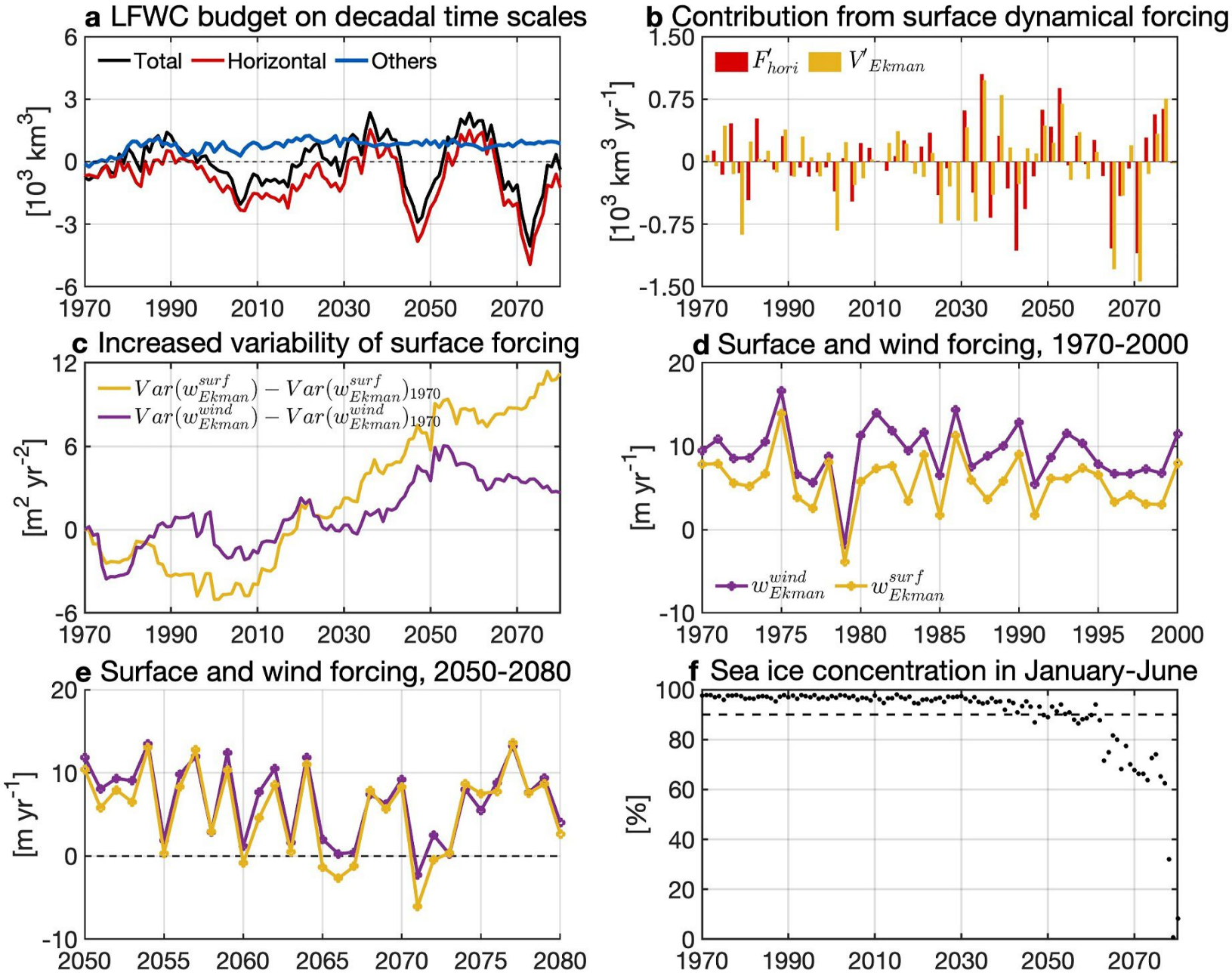

a OSNAP West, HighRes
b OSNAP East, HighRes
c OSNAP Total, HighRes
d OSNAP West, LowRes
e OSNAP East, LowRes
f OSNAP Total, LowRes
Model
Obs
σ_0 [kg m^{-3}]
[Sv]

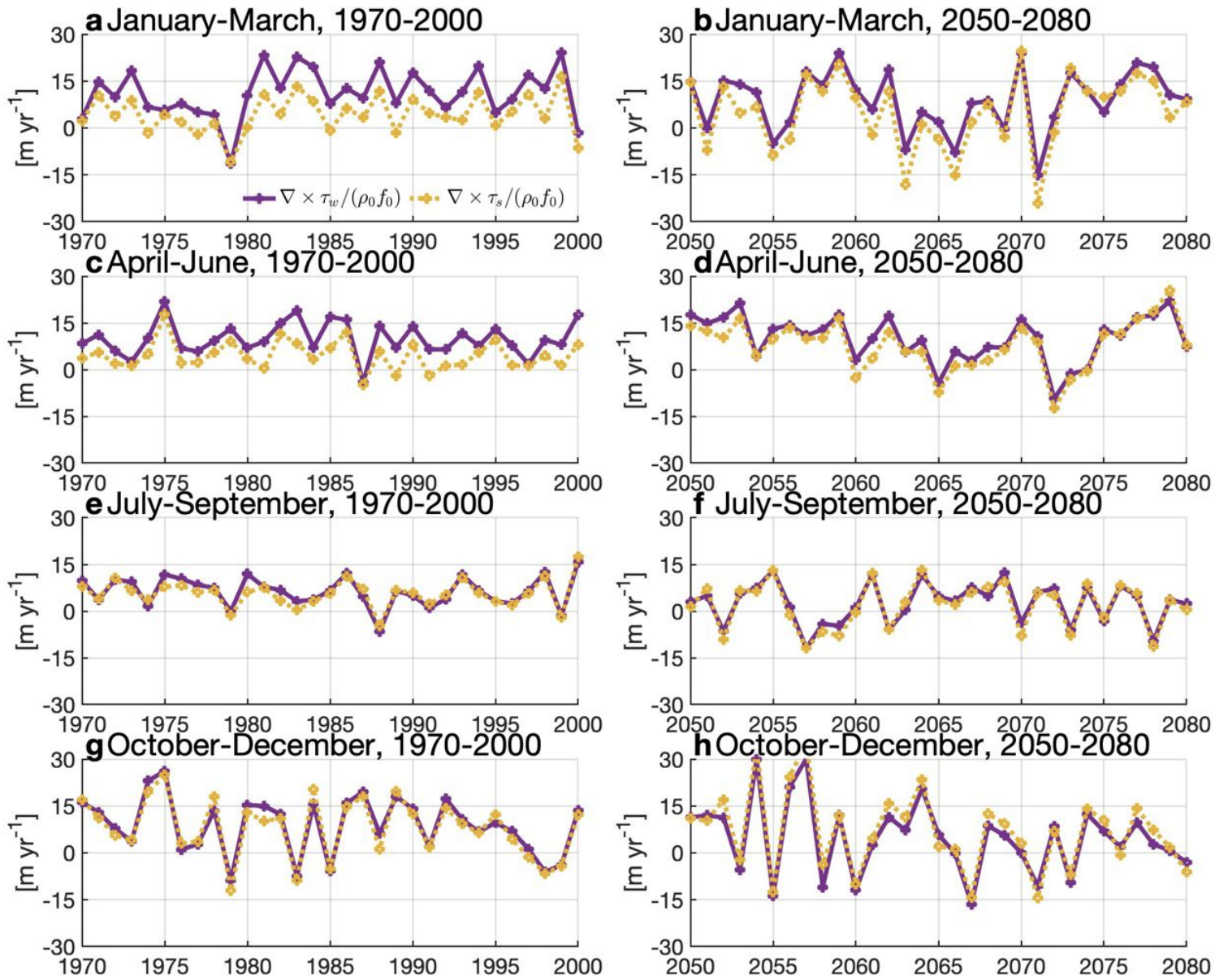

a Potential density, HighRes
Depth [m]
0
200
400
600
800
1000
25.5
26.0
26.5
27.0
27.5
28.0
σ [kg m-3]
2006-2015
2091-2100
b Ocean stratification changes, HighRes
×10-5 s-2
2.0
1.5
1.0
0.5
0.0
-0.5
ΔN2
ΔNS2
ΔNT2
c Potential density, LowRes
Depth [m]
σ [kg m-3]
d Ocean stratification changes, LowRes
×10-5 s-2
ΔN2
ΔNS2
ΔNT2
×10-6
[kg m-2 s-1]
2
1
0
-1
-2
HighRes
LowRes
2020
2040
2060
2080
2100
Year

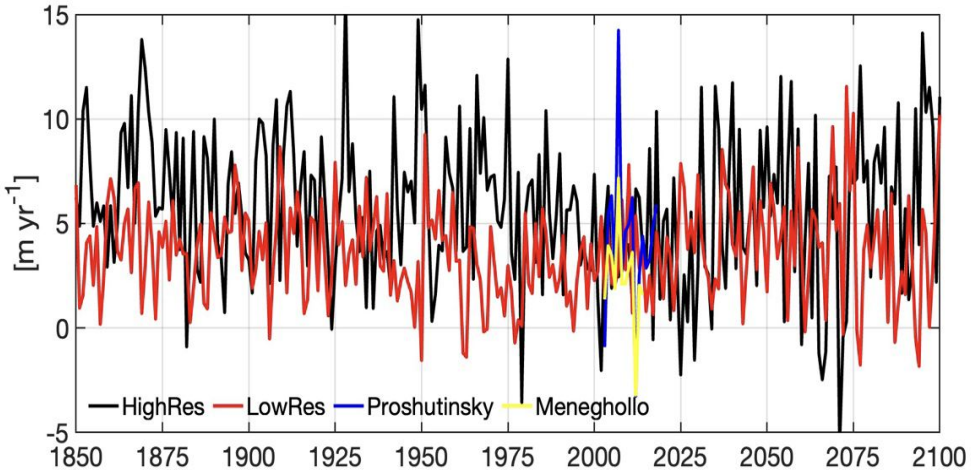

a OSNAP West overturning, HighRes
-55%
2006-2015
2091-2100
σ_2 [kg m^{-3}]
[Sv]
b ΔAMOC, HighRes
Depth [km]
Latitude [°N]
Percentage [%]
c OSNAP West overturning, LowRes
-90%
d ΔAMOC, LowRes

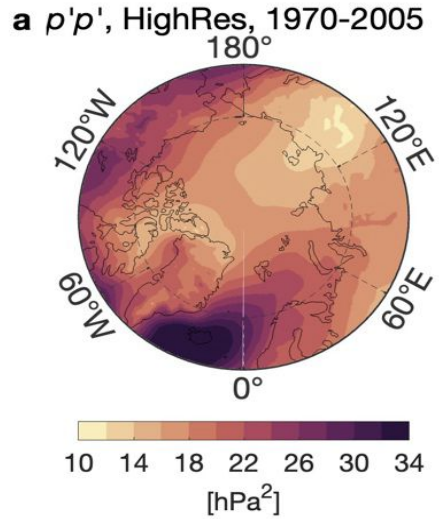

a Percentage changes in OSNAP West overturning
HighRes
LowRes
20
0
-20
-40
-60
-80
-100
[%]
2020
2040
2060
2080
2100
Year
b Percentage changes in OSNAP East overturning
20
0
-20
-40
-60
-80
-100
[%]
2020
2040
2060
2080
2100
Year

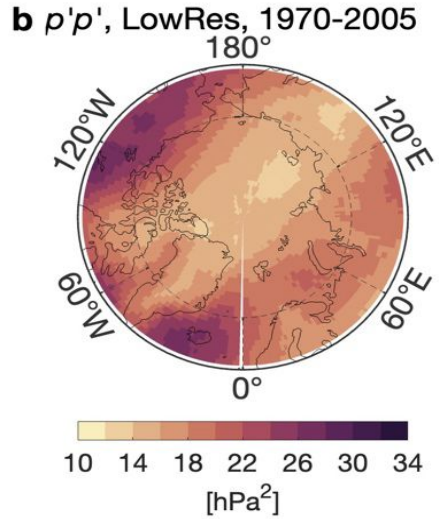

a Long-term freshwater sources and sinks
$\overline{F}_{sinks} : (\overline{F}_{hori} - \overline{F}_{Ekman}) + \overline{F}_{bot} + \overline{F}_{ssh} + \overline{F}_{turb}$
$\overline{F}_{hori} - \overline{F}_{Ekman}$
$\overline{F}_{sources} : \overline{F}_{surf} + \overline{F}_{Ekman}$
$[10^3\ km^3\ yr^{-1}]$
b Long-term freshwater sources
$\overline{F}_{sources}$
$\overline{F}_{Ekman}$
$\overline{F}_{surface}$
$[10^3\ km^3\ yr^{-1}]$
c Change of surface freshwater flux
$\overline{F}_{surface}$
$\overline{F}_{ice}$
$\overline{F}_{pme}$
$\overline{F}_{melt}$
$\Delta\overline{V}_{ice}^{gyre}$
$[10^3\ km^3\ yr^{-1}]$
d Change of wind-driven convergence
$\overline{F}_{Ekman}$
$\overline{F}_{Ekman}^{v'}$
surface forcing
wind forcing
$[10^3\ km^3\ yr^{-1}]$
$[m\ yr^{-1}]$

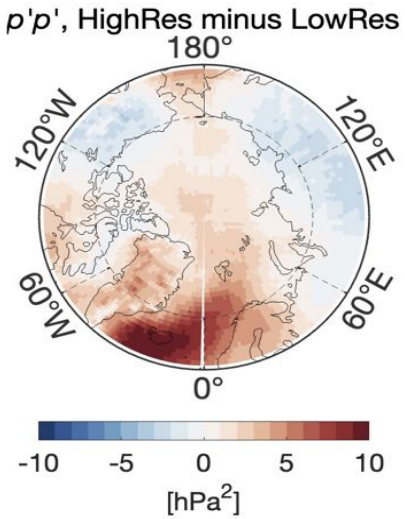

a LFWC budget on decadal time scales
Total
Horizontal
Others
[10^3 km^3]
b Contribution from surface dynamical forcing
F'_hori
V'_Ekman
[10^3 km^3 yr^-1]
c Increased variability of surface forcing
Var(w^surf_Ekman) − Var(w^surf_Ekman)_1970
Var(w^wind_Ekman) − Var(w^wind_Ekman)_1970
[m^2 yr^-2]
d Surface and wind forcing, 1970-2000
w^wind_Ekman
w^surf_Ekman
[m yr^-1]
e Surface and wind forcing, 2050-2080
[m yr^-1]
f Sea ice concentration in January-June
[%]

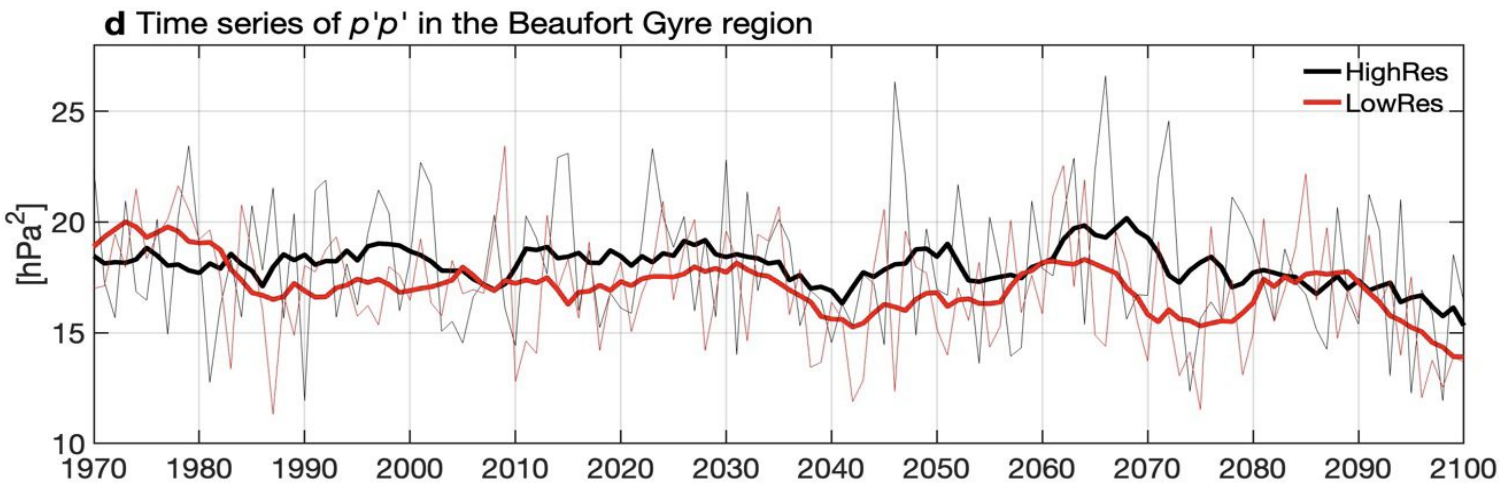

a January-March, 1970-2000
b January-March, 2050-2080
c April-June, 1970-2000
d April-June, 2050-2080
e July-September, 1970-2000
f July-September, 2050-2080
g October-December, 1970-2000
h October-December, 2050-2080
[m yr^{-1}]
30
15
0
-15
-30
1970
1975
1980
1985
1990
1995
2000
2050
2055
2060
2065
2070
2075
2080
$\nabla \times \tau_w/(\rho_0 f_0)$
$\nabla \times \tau_s/(\rho_0 f_0)$


15
10
5
0
-5
[m yr^{-1}]
HighRes
LowRes
Proshutinsky
Meneghollo
1850
1875
1900
1925
1950
1975
2000
2025
2050
2075
2100


a p'p', HighRes, 1970-2005
180°
120°W
120°E
60°W
60°E
0°
10 14 18 22 26 30 34
[hPa^2]


b p'p', LowRes, 1970-2005
180°
120°W
120°E
60°W
60°E
0°
10 14 18 22 26 30 34
[hPa^2]


c p'p', HighRes minus LowRes
180°
120°W
120°E
60°W
60°E
0°
-10 -5 0 5 10
[hPa^2]


d Time series of p'p' in the Beaufort Gyre region
HighRes
LowRes
25
20
15
10
[hPa^2]
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100