Potential Impacts of Marine Cloud Brightening in the Arctic System and Beyond

2026 PCWG Workshop

Walker Lee, Clare Singer, David Clemens-Sewall, Courtney Payne

University of Colorado
Boulder | Colorado Springs | Denver | Anschutz Medical Campus
Grantham Foundation
for the Protection of the Environment
NSF
NCAR
OPERATED BY UCAR

- Andrew Gettelman and Marika Holland (PIs)
- Clare Singer (clouds)
- Walker Lee (simulations)
- David Clemens-Sewall (sea ice)
- Courtney Payne (ecology)
- Laura Landrum (polar climate)
- Erin Emme (cold cloud processes)
- +more collaborators at NCAR and beyond

Jack Chen, Simone Tilmes, Christina McCluskey, Kanishk Gohil, Jasper Kok, Xia Li; w/ funding from QCF and Simons Foundation

Outline

- Motivation
- Experimental Setup
- Global Impacts
- Atmospheric and Surface Energy Budget Impacts
- Snow, Sea Ice, & Ocean Impacts
- Ecosystem Impacts
- Conclusions and Next Steps

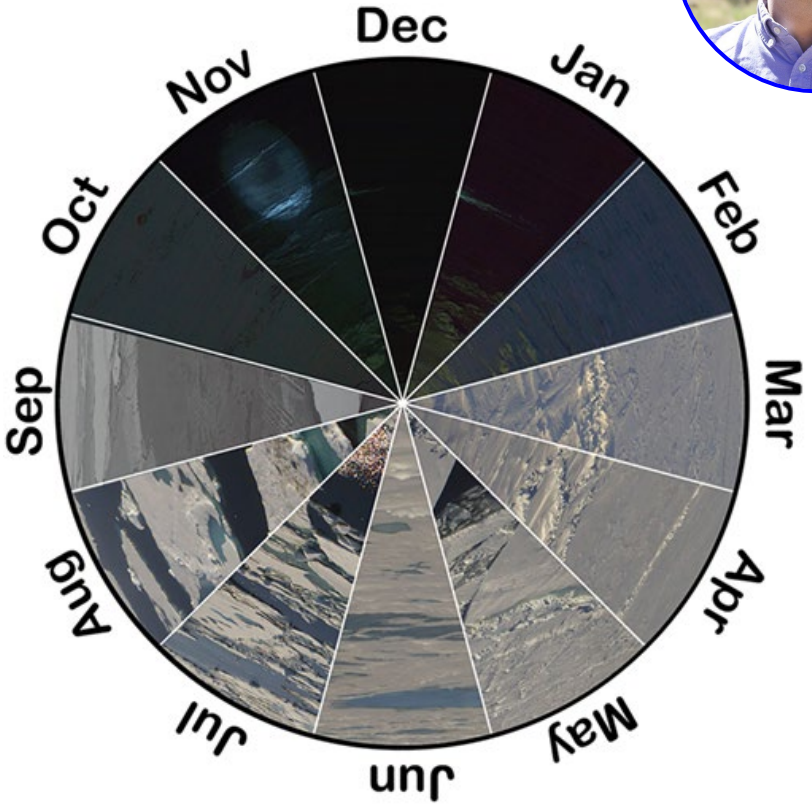
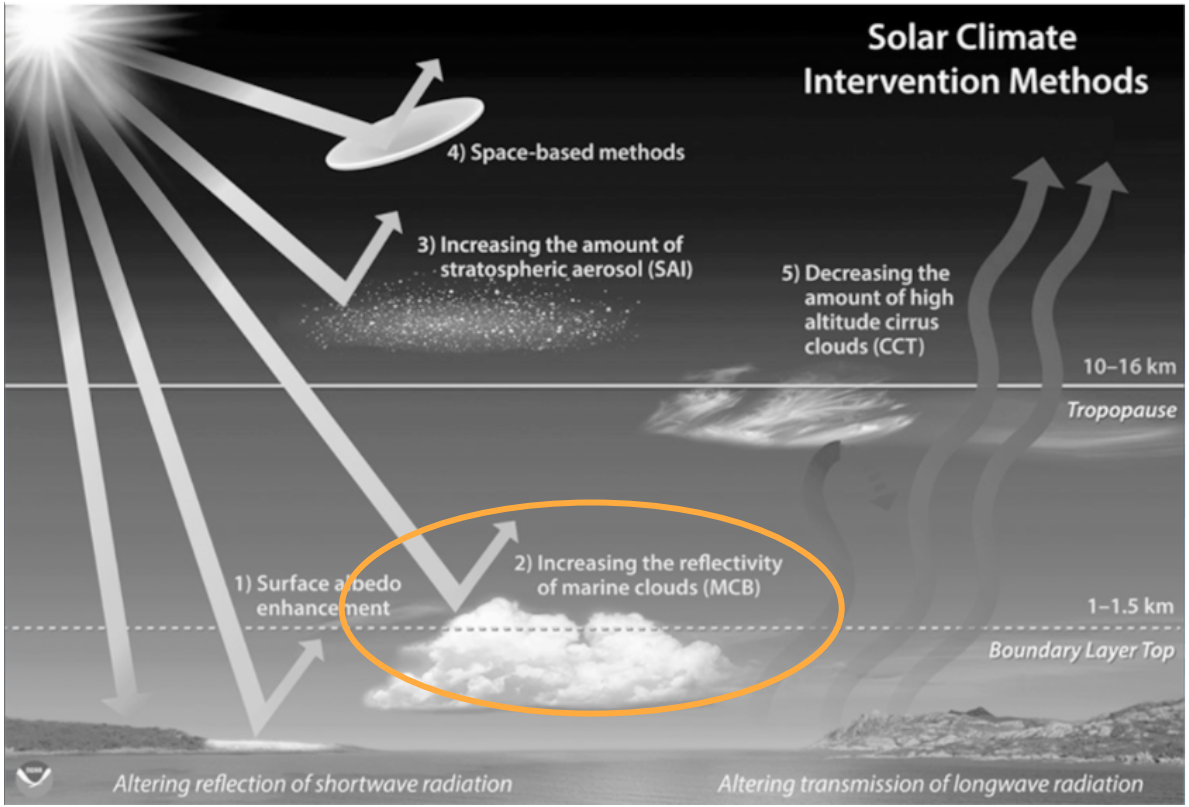


Figure Nicolaus et al., 2022

Introduction: Climate Intervention

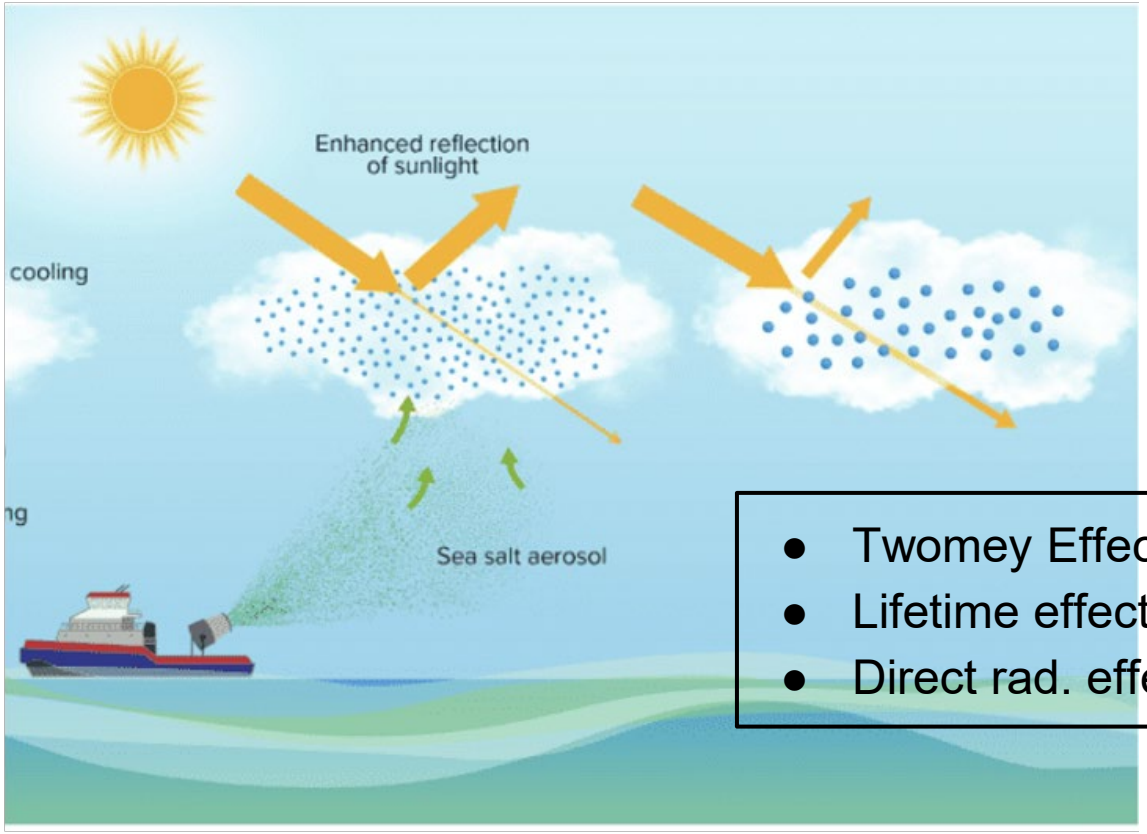
"Solar radiation modification"

"Solar geoengineering"



NOAA, Dr. Chelsea Thompson

Introduction: Climate Intervention



- Twomey Effect
- Lifetime effects
- Direct rad. effect

NOAA, Scientists detail research to assess viability and risks of marine cloud brightening

Experimental setup: model

- CESM2-CAM6 simulations
- SSP3-7.0 scenario
- Model years 2035-2070
- smbb, less-melt, 4p2z modifications
- 5 baseline ensemble members
- 9 MCB simulations

Moderate warming

Near future; similar timeline to other MCB/SAI simulations

Smoothed biomass burning

Ocean Biogeochemistry

Indirectly increase sea ice albedo

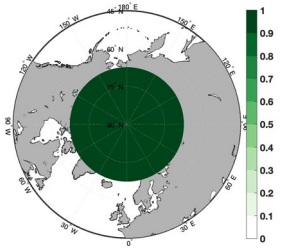
Cloud droplet number concentration (#/cm^3)

Perturb N_d in low clouds in select grid cells

Experimental setup: seeding maps

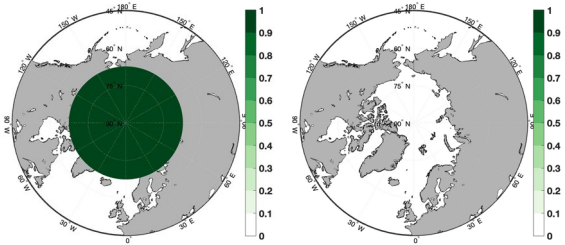
“ANN”

Year-round seeding
All grid cells >67°N



“MJJAS”

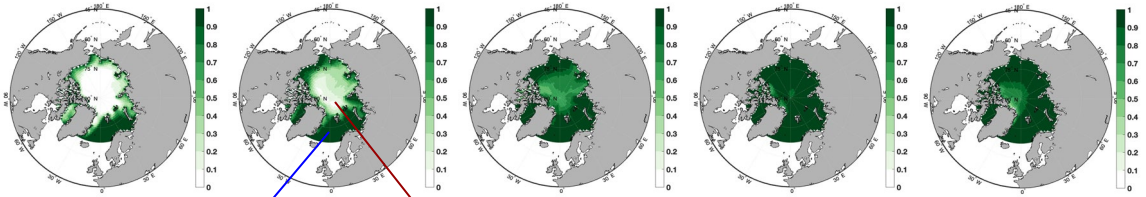
Summer-only seeding
All grid cells >67°N



May-Sept Oct-Apr

“Dynamic Mask”

Summer-only seeding, >67°N;
exclude SIC ≥ 90%, land ≥ 50%
Change mask each timestep



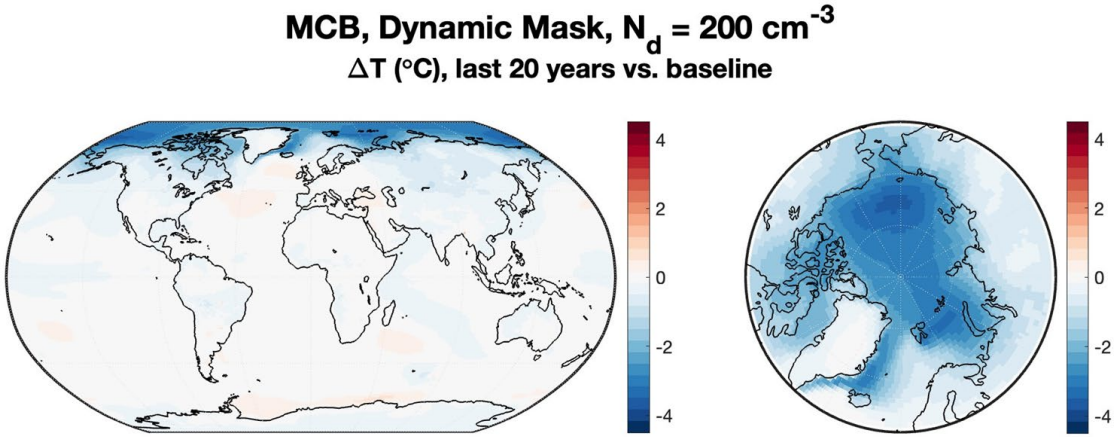
May June July Aug Sept

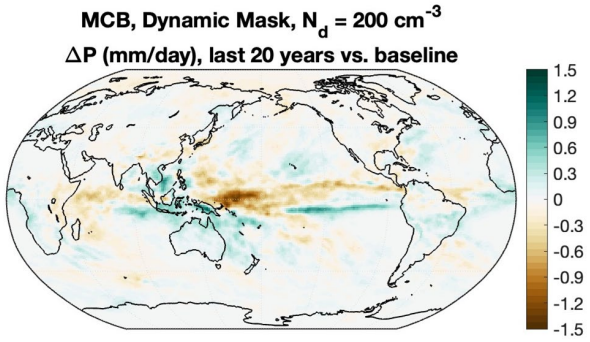
Dark green: seeded most/all of the time

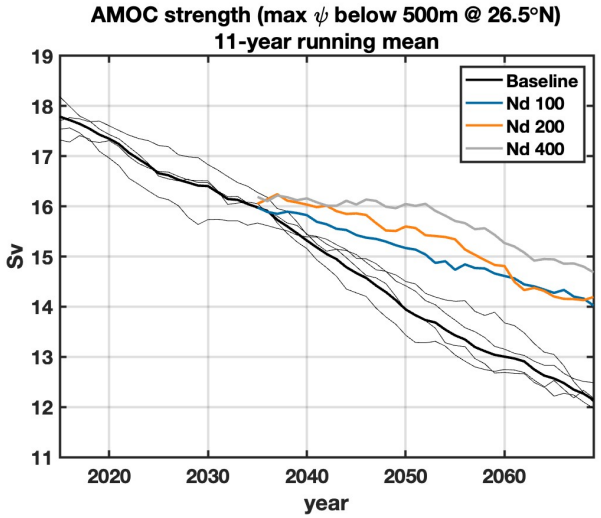
Light green/white: seeded less often

Each strategy: $N_d \rightarrow$ 100, 200, 400 #/cm^3 simulations

How much does this cool the planet in CESM2?







Outline

- Motivation
- Experimental Setup
- Global Impacts
- Atmospheric and Surface Energy Budget Impacts
- Snow, Sea Ice, & Ocean Impacts
- Ecosystem Impacts
- Conclusions and Next Steps

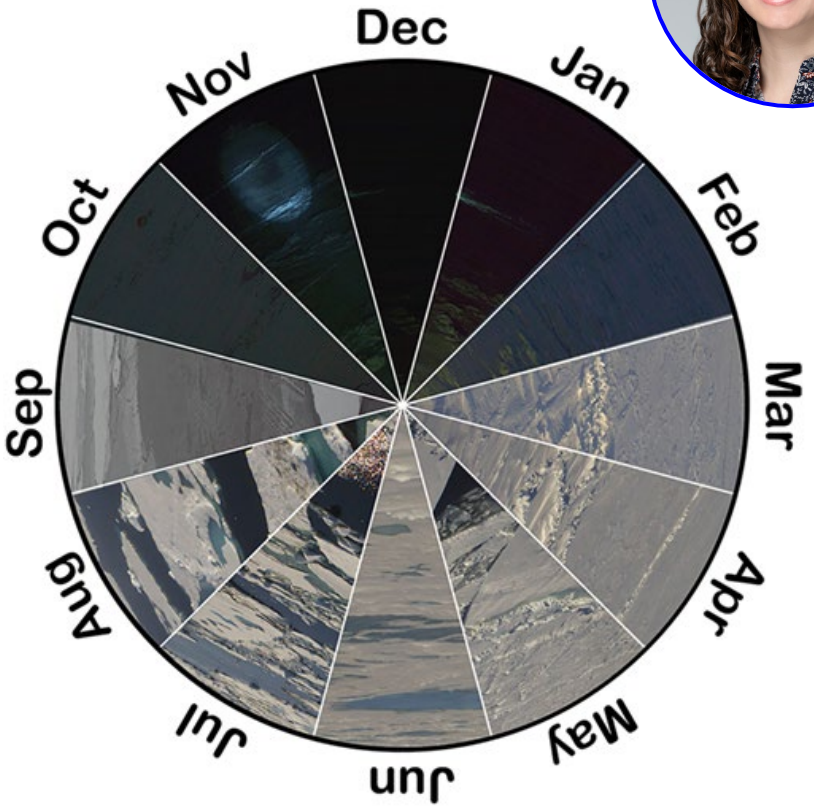
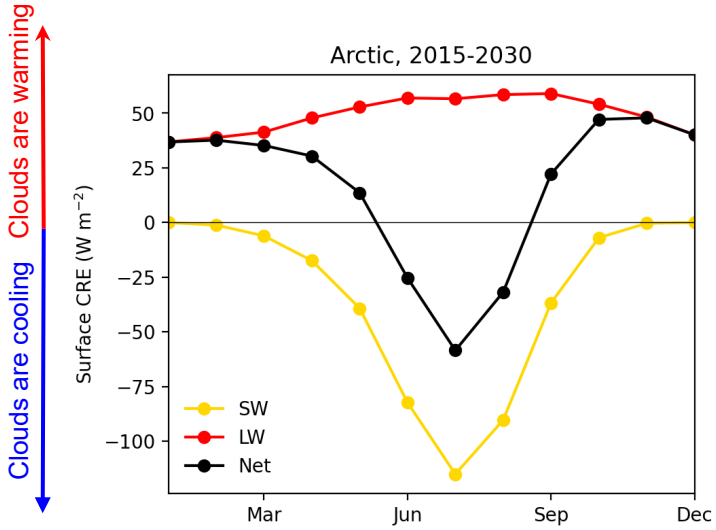
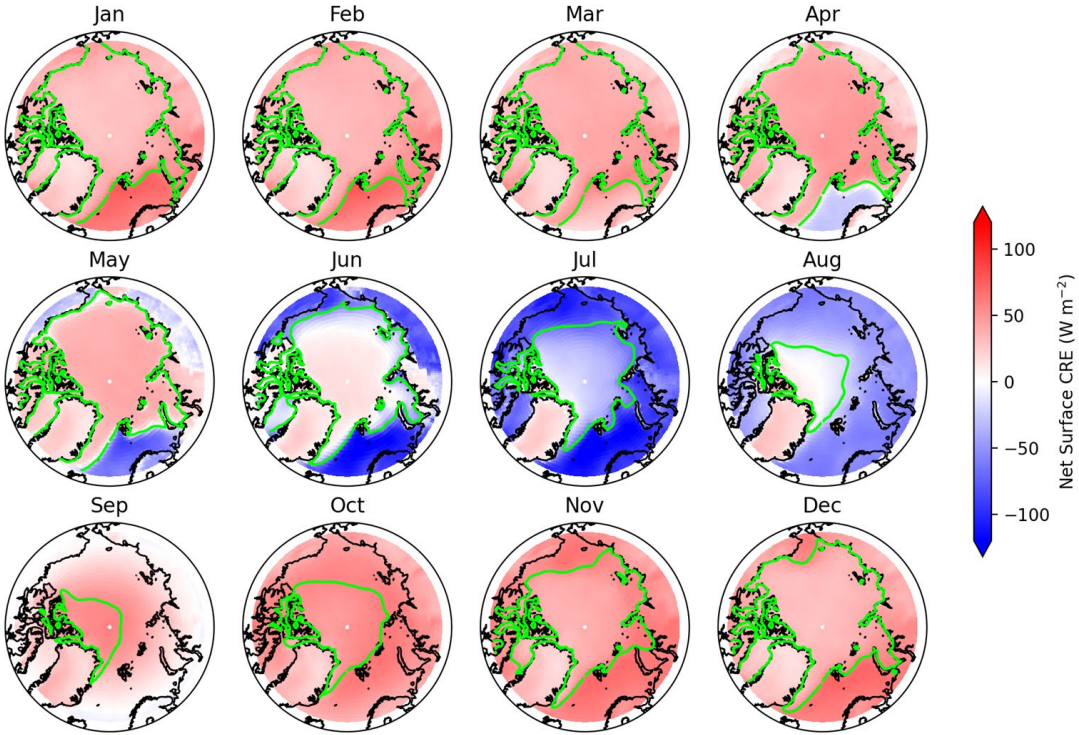


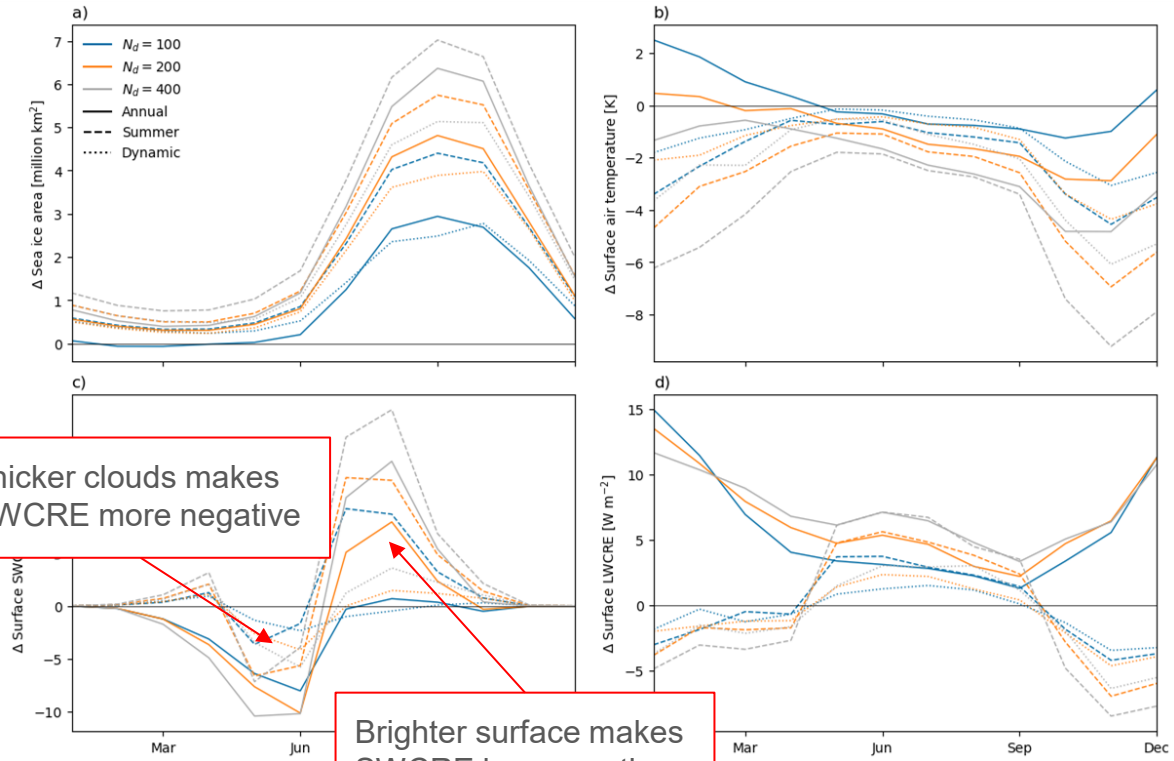
Figure Nicolaus et al., 2022

Clouds currently cool the Arctic only in summer, mostly over open water and MIZ





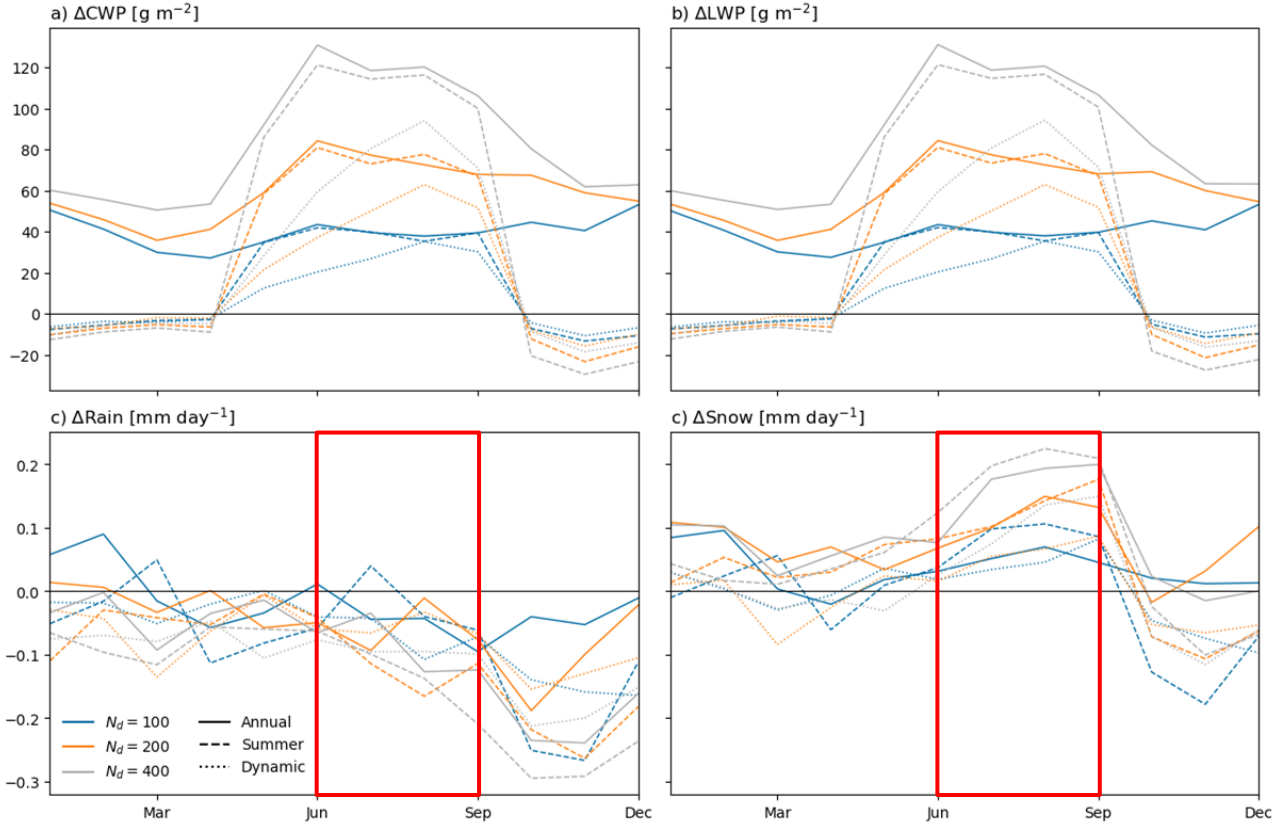
Seasonality of changes



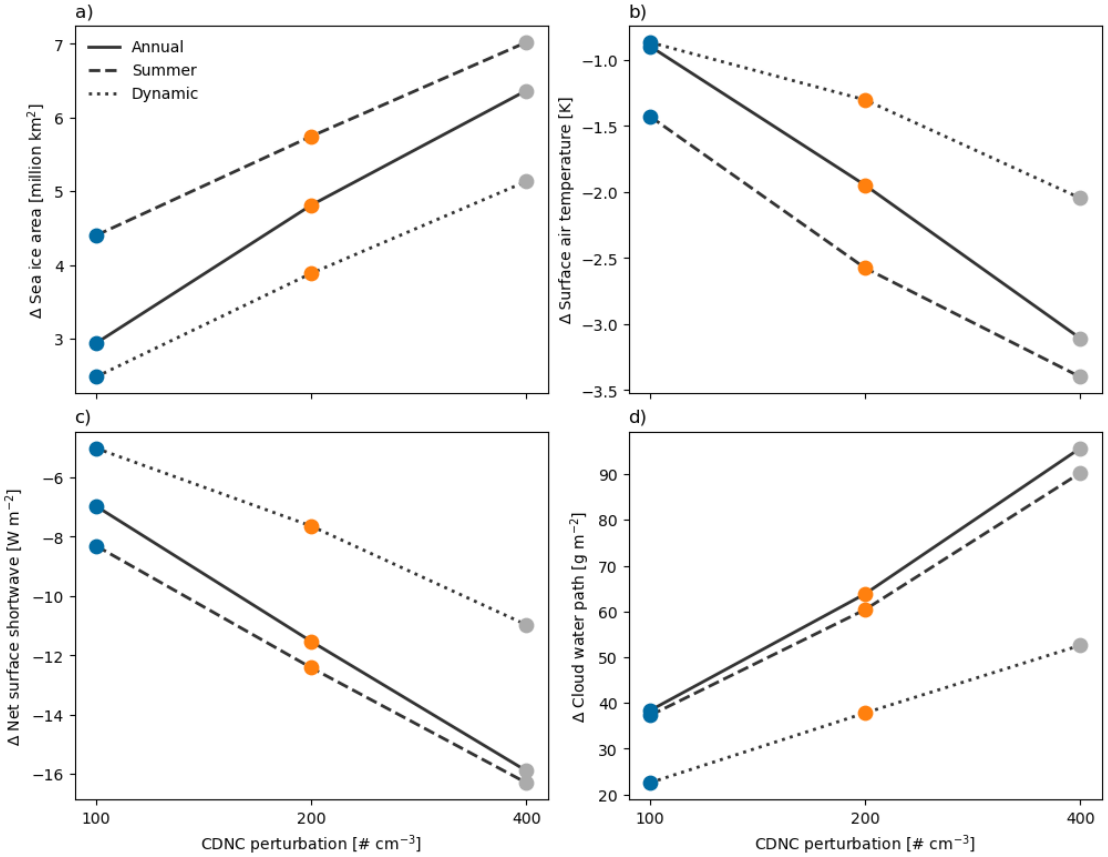
- Largest changes in sea ice area in summer/fall.
- Summer-only perturbations eliminate unwanted winter warming via LW effects.
- Surface cover, not just cloud cover, influence CRE.

Changes in cloud and precipitation amount

- Nearly all changes in cloud water are in liquid phase.
- Shift in summer precipitation from rain to snow.
- Less total precipitation in fall.



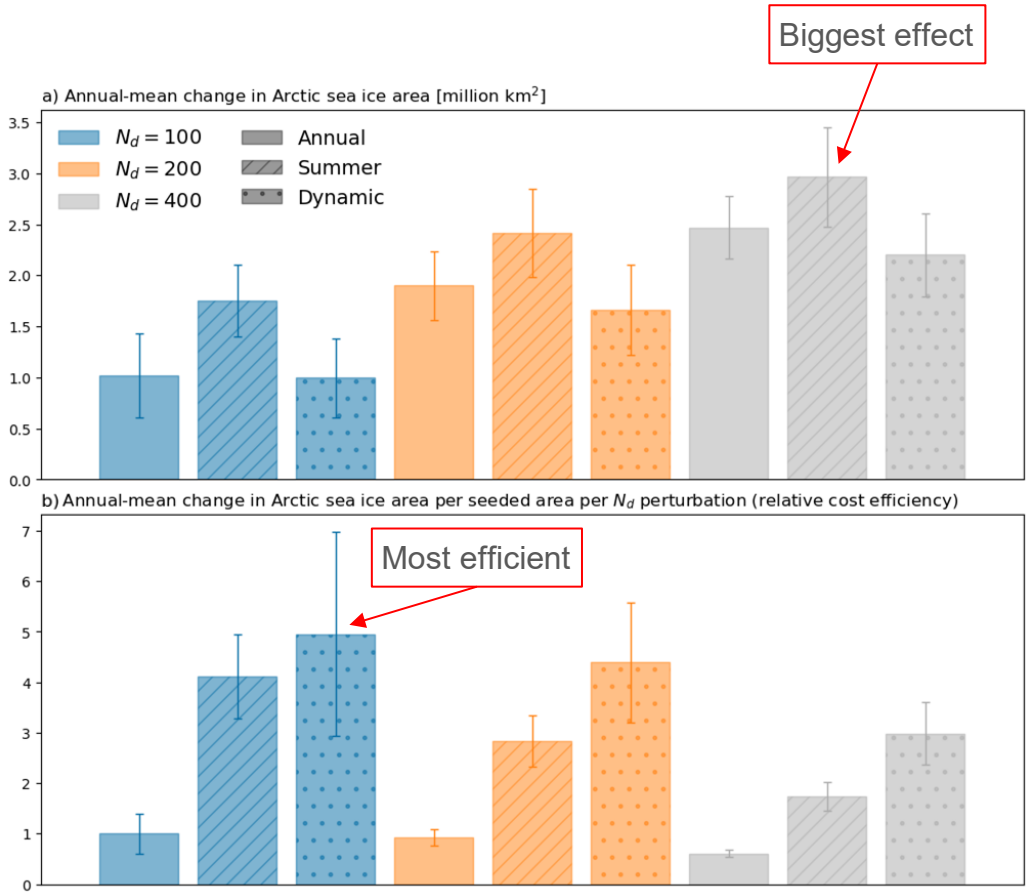
Many responses are linear for *Nd* doubling



Effect vs. efficiency

Summer-only, dynamic (SIC<90) perturbation is most efficient.

**Efficiency = change in Arctic sea ice area per total seeding (area * Nd)*



Atmosphere & Radiation Takeaways

1. Cloud perturbations are most effective during summer months
2. Perturbations are most efficient over open water
3. Cooling shifts precipitation from rain to snow during summer months, but decreases total precipitation during fall
4. Many climate variables respond linearly to doubling of *Nd*

Outline

- Motivation
- Experimental Setup
- Global Impacts
- Atmospheric and Surface Energy Budget Impacts
- Snow, Sea Ice, & Ocean Impacts
- Ecosystem Impacts
- Conclusions and Next Steps

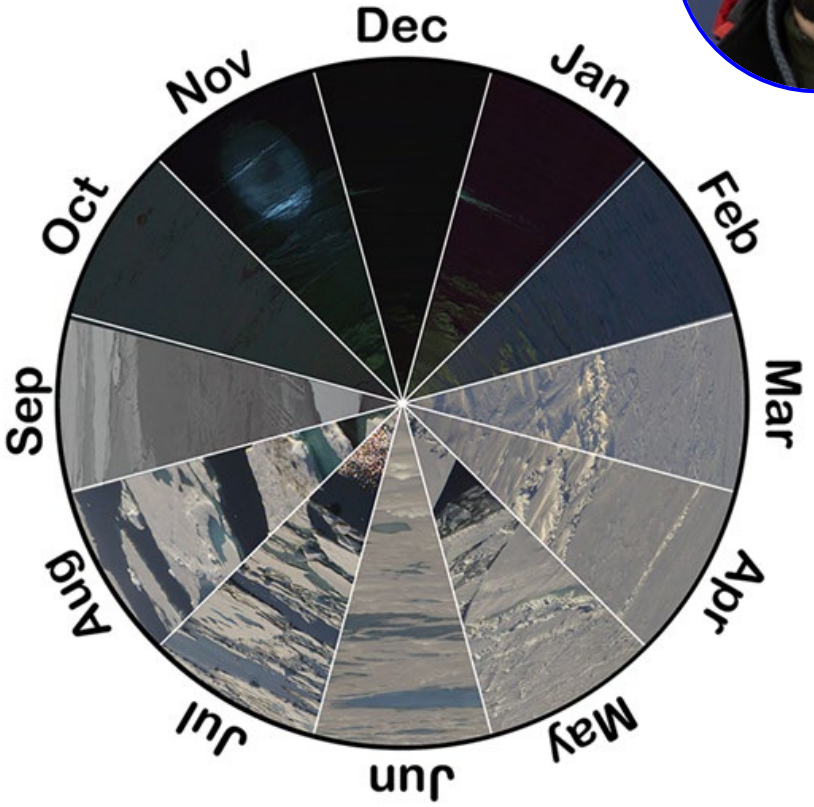
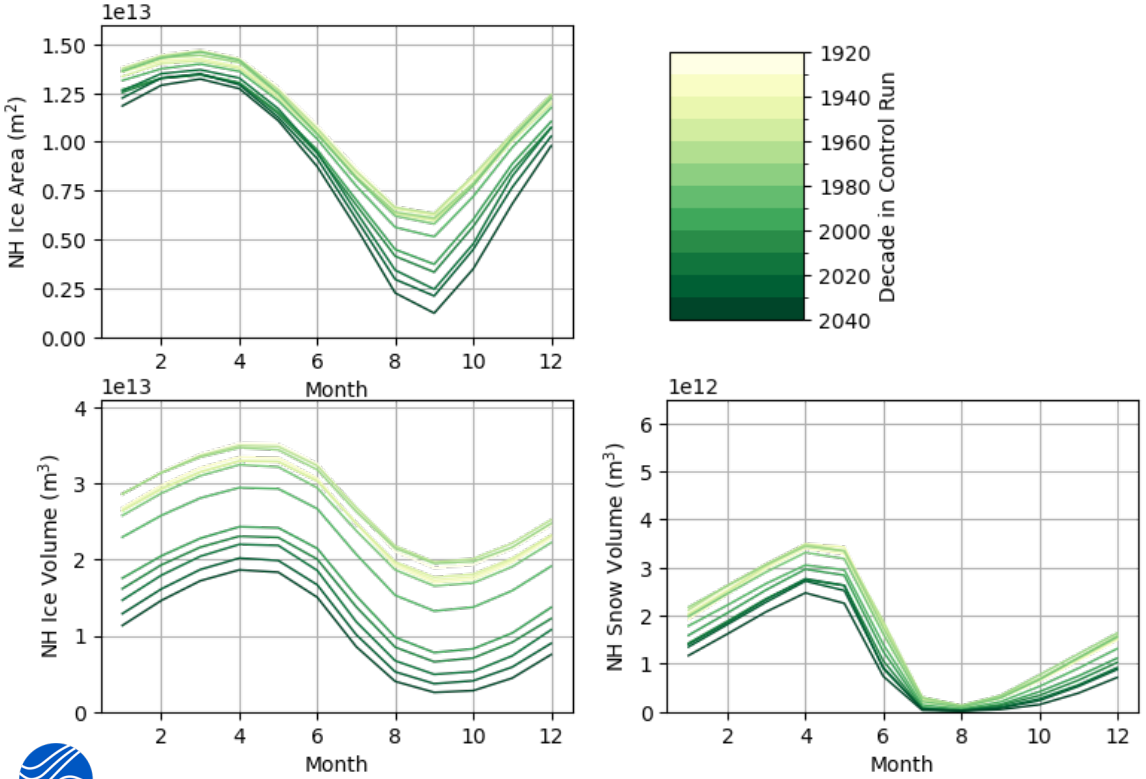
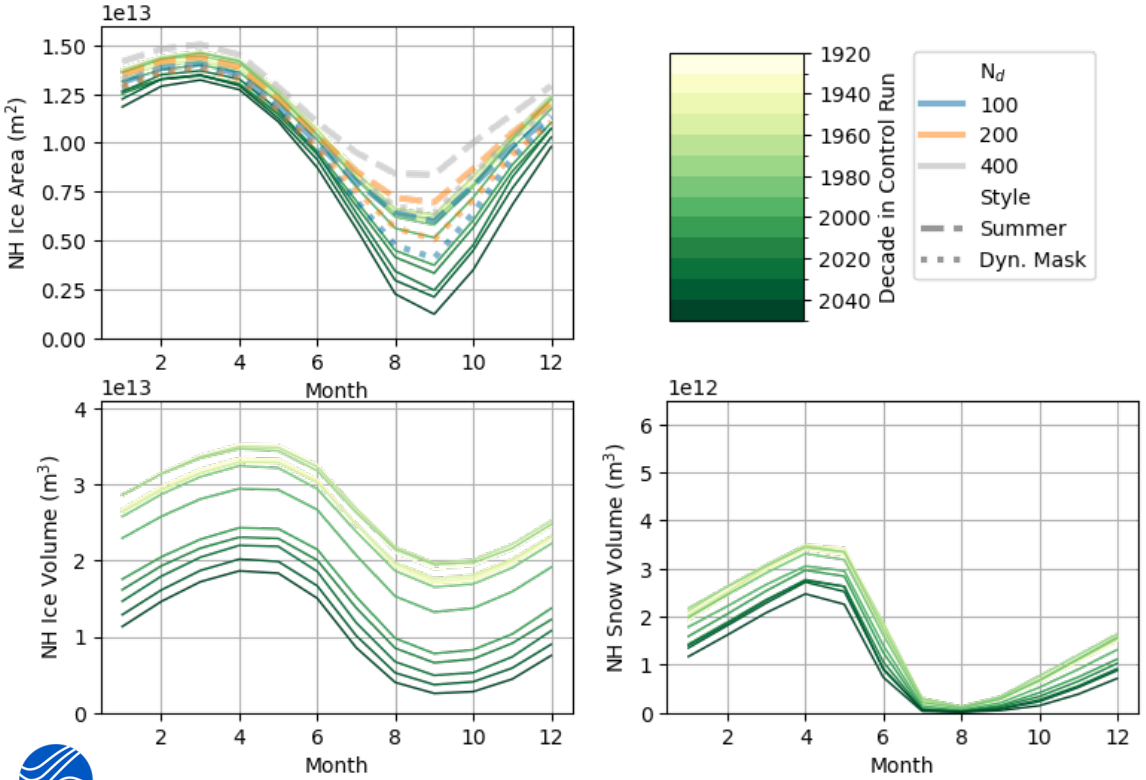


Figure Nicolaus et al., 2022

Annual Cycle of North Hemisphere Snow and Sea Ice



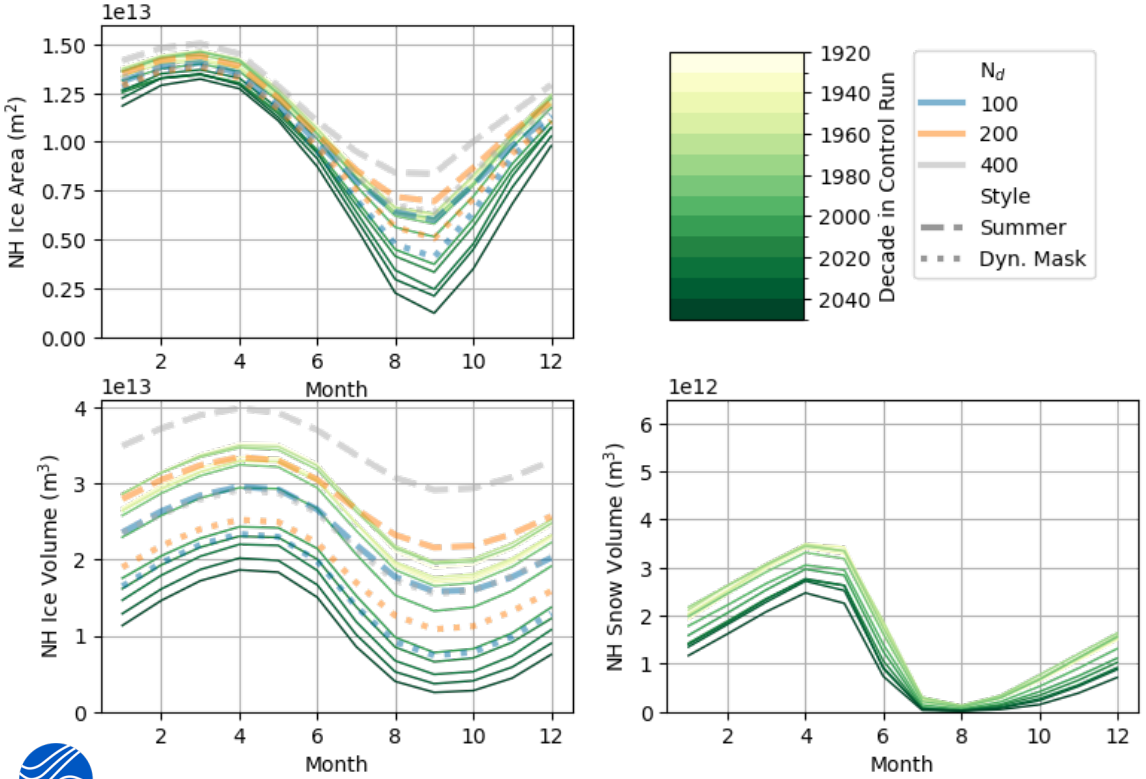
Annual Cycle of North Hemisphere Snow and Sea Ice



Key Points:

1. N_d 100 & 200 perturbations return ice area to historical

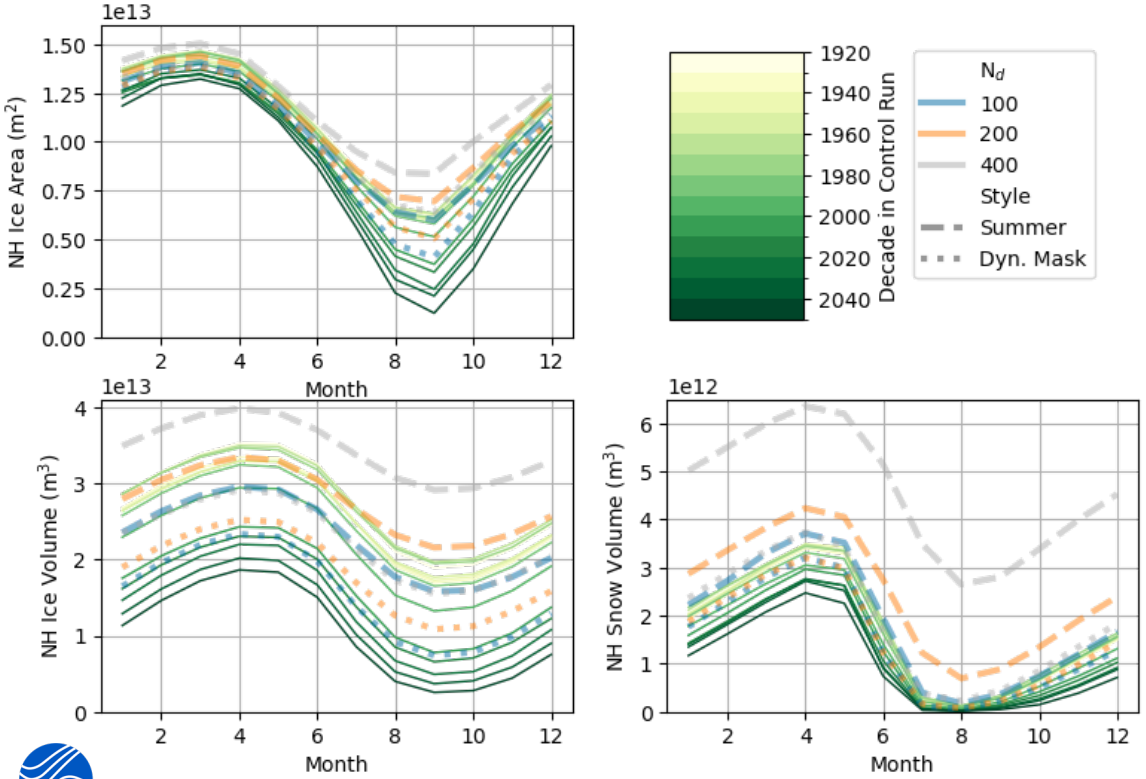
Annual Cycle of North Hemisphere Snow and Sea Ice



Key Points:

1. N_d 100 & 200 perturbations return ice area to historical
2. Seasonal cycle of ice volume is dampened relative to historical

Annual Cycle of North Hemisphere Snow and Sea Ice



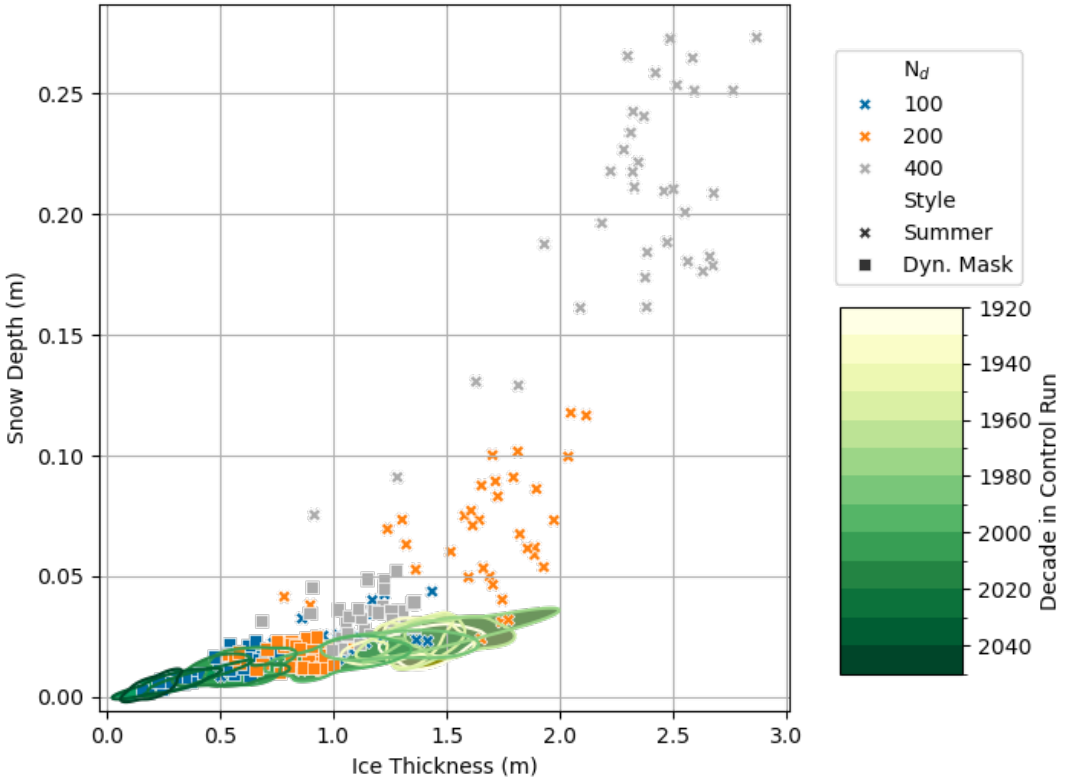
Key Points:

1. N_d 100 & 200 perturbations return ice area to historical
2. Seasonal cycle of ice volume is dampened relative to historical
3. N_d 200 & 400 produce unprecedented perennial snowpacks

Historically Unprecedented Sept. Snow and Ice States

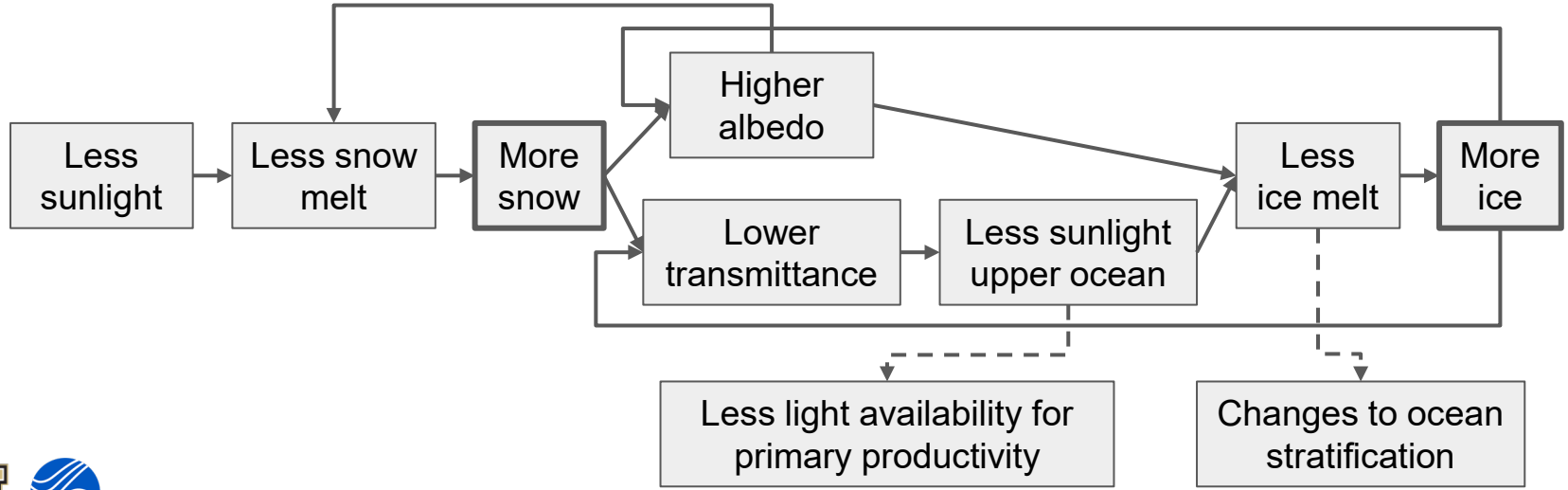
The N_d 200 & 400 Summer perturbations and the 400 Dynamic Mask produce snow and sea ice states with historically unprecedented deep snow.

Figure shows 1940s in the perturbations for the ocean north of 67N. Differences are most dramatic in Central Arctic (not shown)

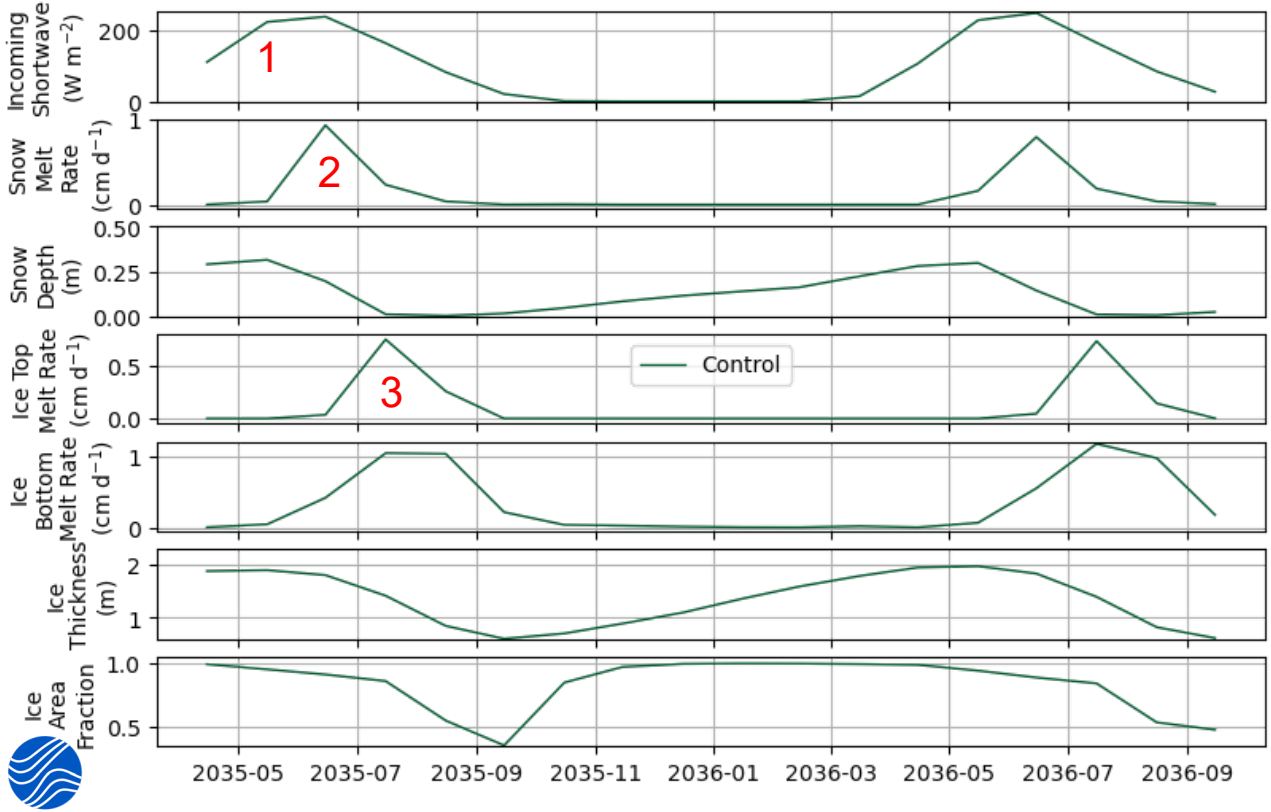


Hypothesis

A reduction in incoming sunlight decreases snow melt rates, kicking off a positive feedback that results in historically unprecedented summertime snow conditions (high), light availability in the upper ocean (low), and changes to upper ocean stratification.

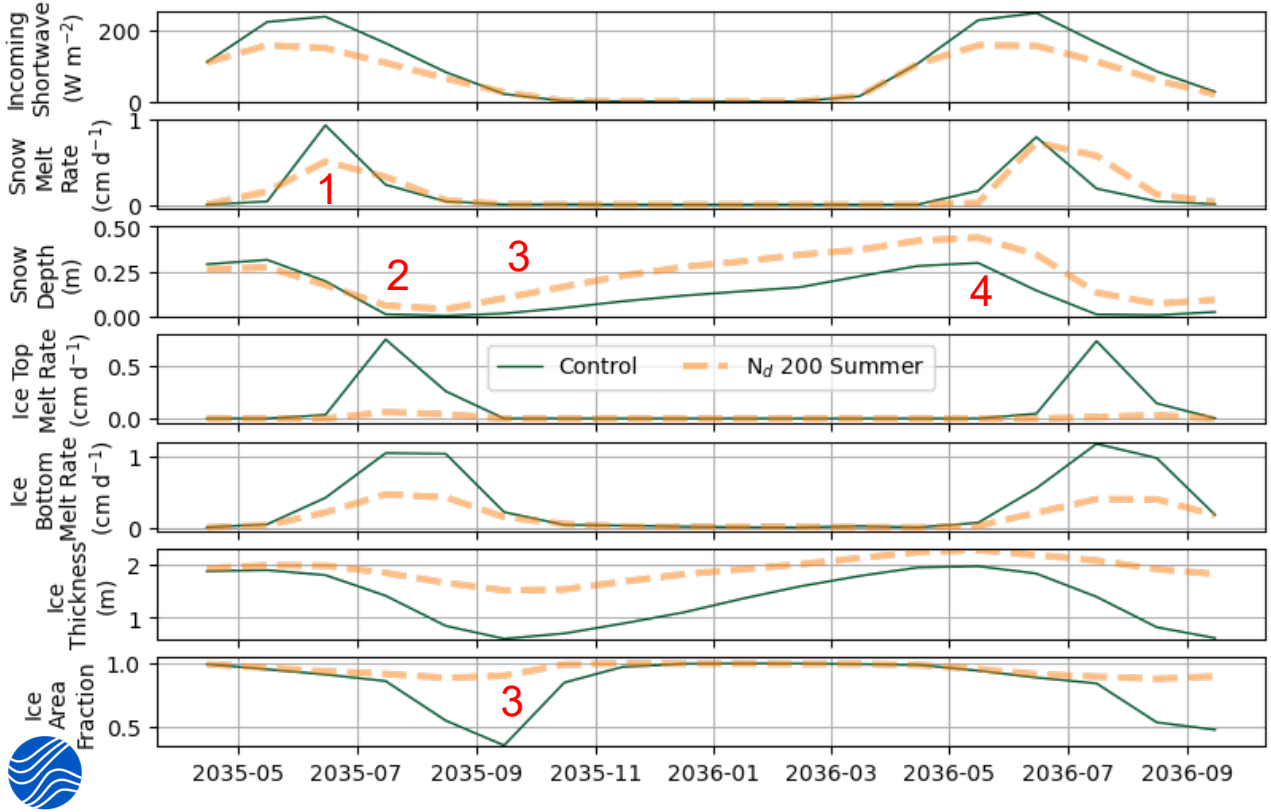


Temporal Evolution in Central Arctic



1. Incoming shortwave seasonally increases
2. Snow melts (~1 month after shortwave)
3. Ice top starts melting (~1 month after snow melt)

Temporal Evolution in Central Arctic

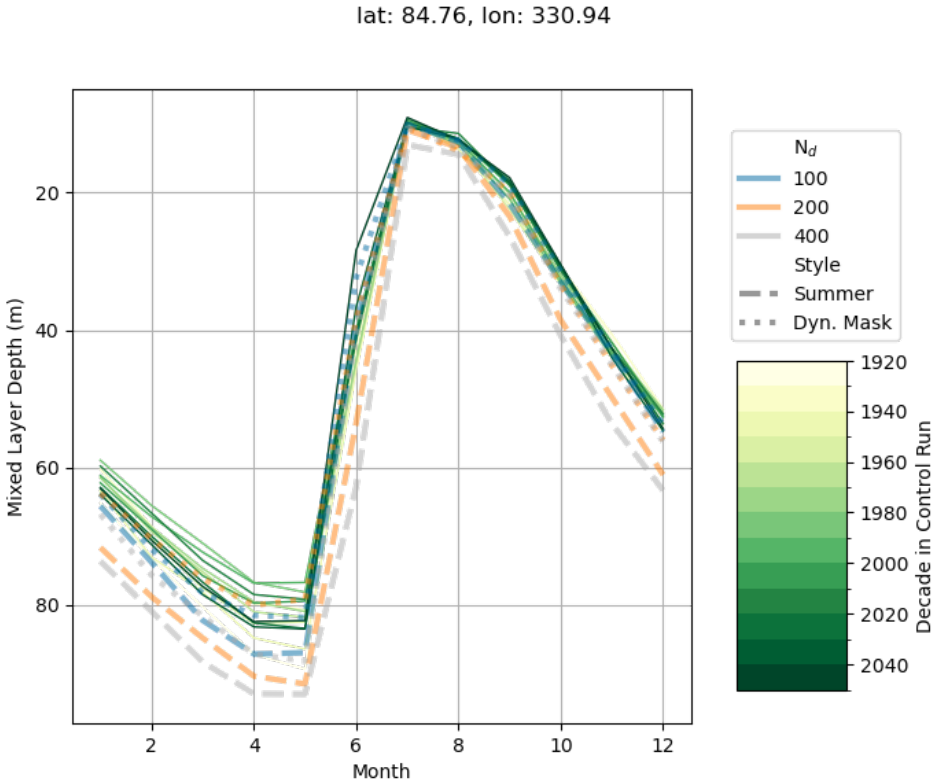


1. Snow melt rate is much lower
2. Snow persists through summer, shutting off ice top melt (also reduces bottom melt)
3. Persistent snow and more ice area in Fall lead to deeper snow throughout Fall and Winter
4. Following melt season starts with much deeper snow (interannual positive feedback)

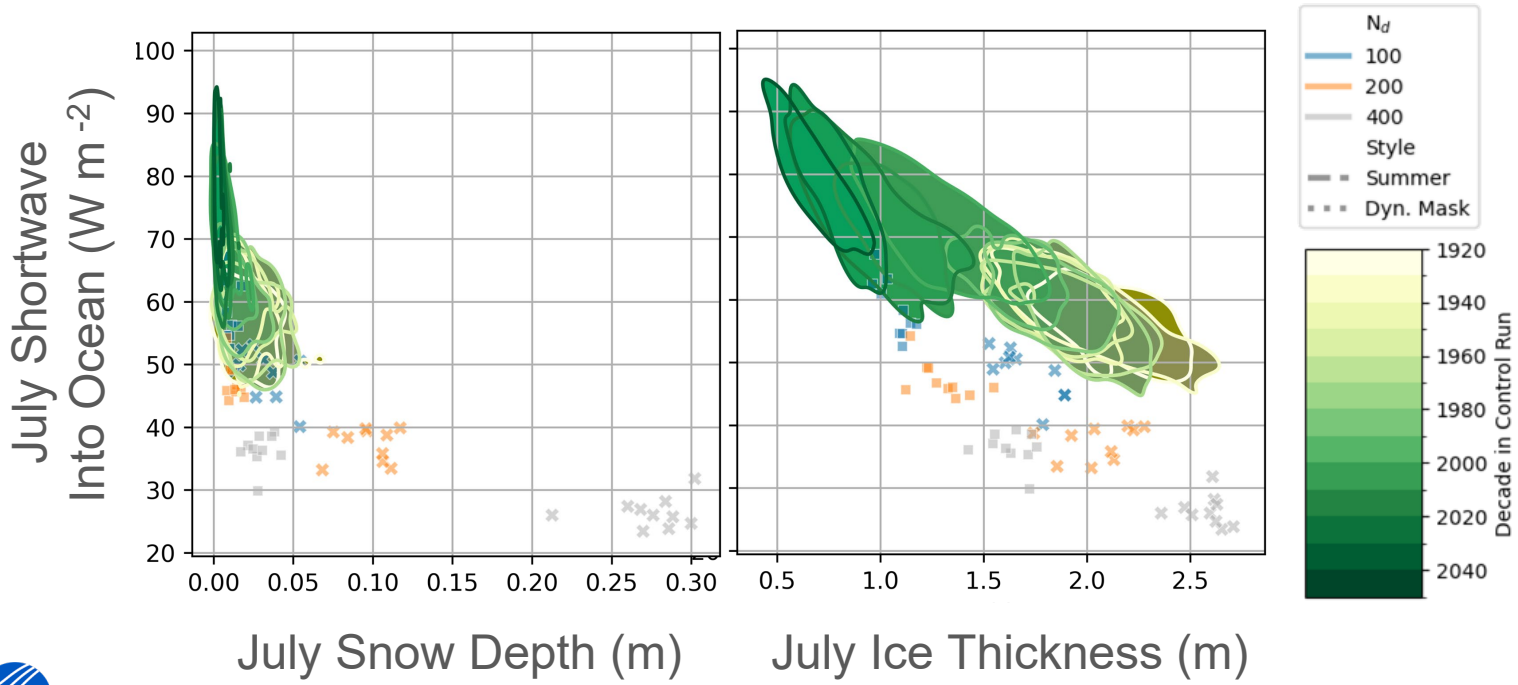
Ocean Stratification Changes

Ocean mixed layer in the Central Arctic in perturbed runs is generally deeper.

Especially in June, when seasonal shoaling due to freshwater from ice melt is delayed



Historically Unprecedented Low Light in Upper Ocean



Snow, Sea Ice, & Ocean Impacts Takeaways

- Perturbations can cause decreases in summertime snow melt rates, resulting in historically-unprecedented perennial snow conditions.
- This produces a dampened annual cycle of ice melt and growth, which changes deepens and delays shoaling of the ocean mixed layer depth.
- Perennial snowpacks also produce historically-unprecedented low levels of sunlight in the upper ocean.

Outline

- Motivation
- Experimental Setup
- Global Impacts
- Atmospheric and Surface Energy Budget Impacts
- Snow, Sea Ice, & Ocean Impacts
- Ecosystem Impacts
- Conclusions and Next Steps

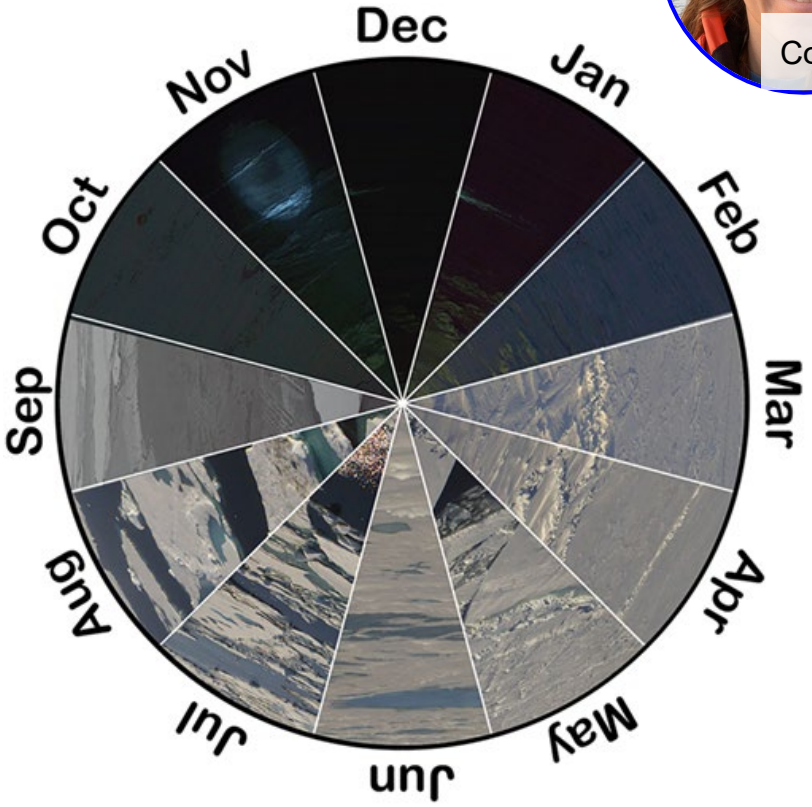
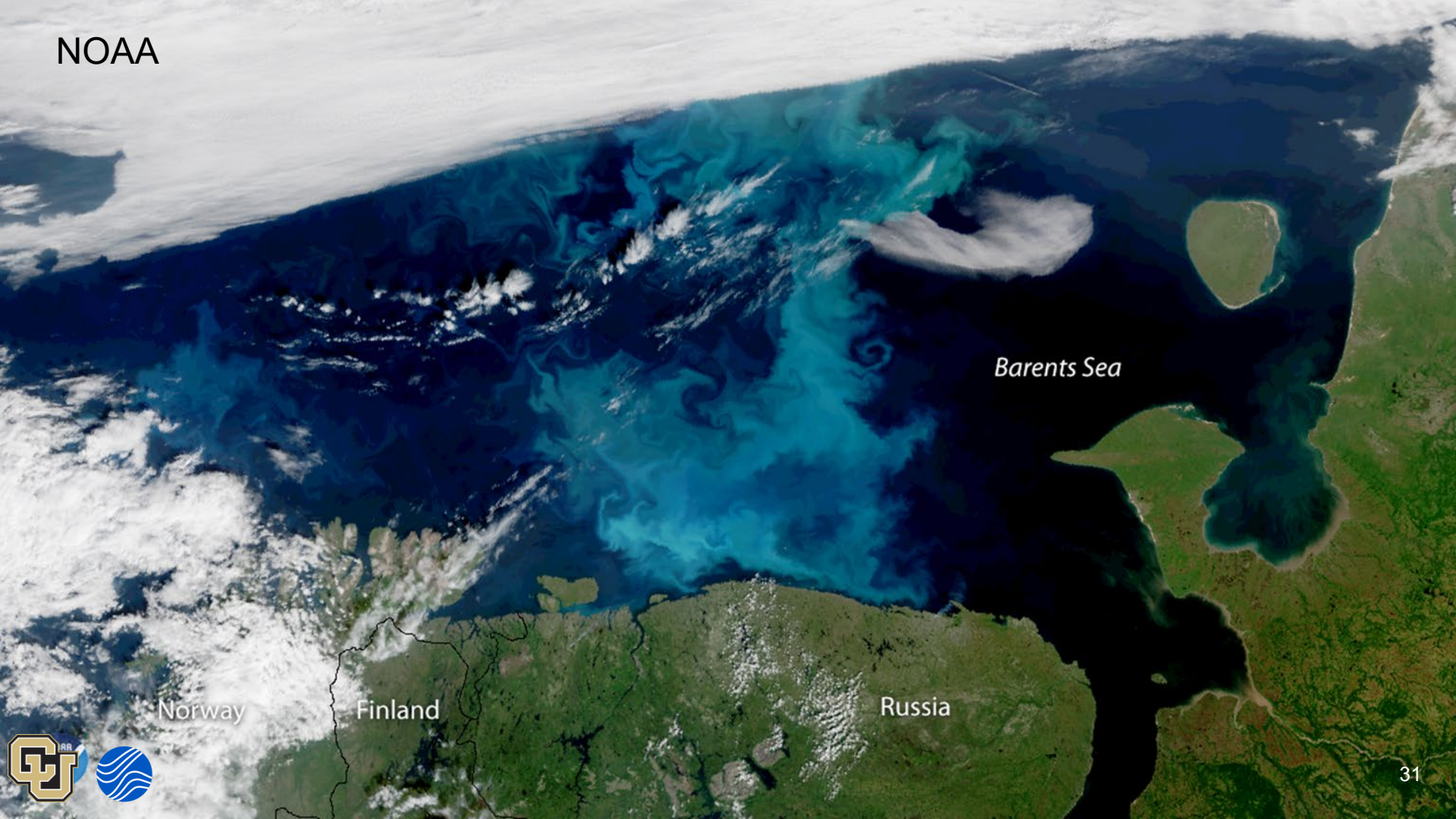
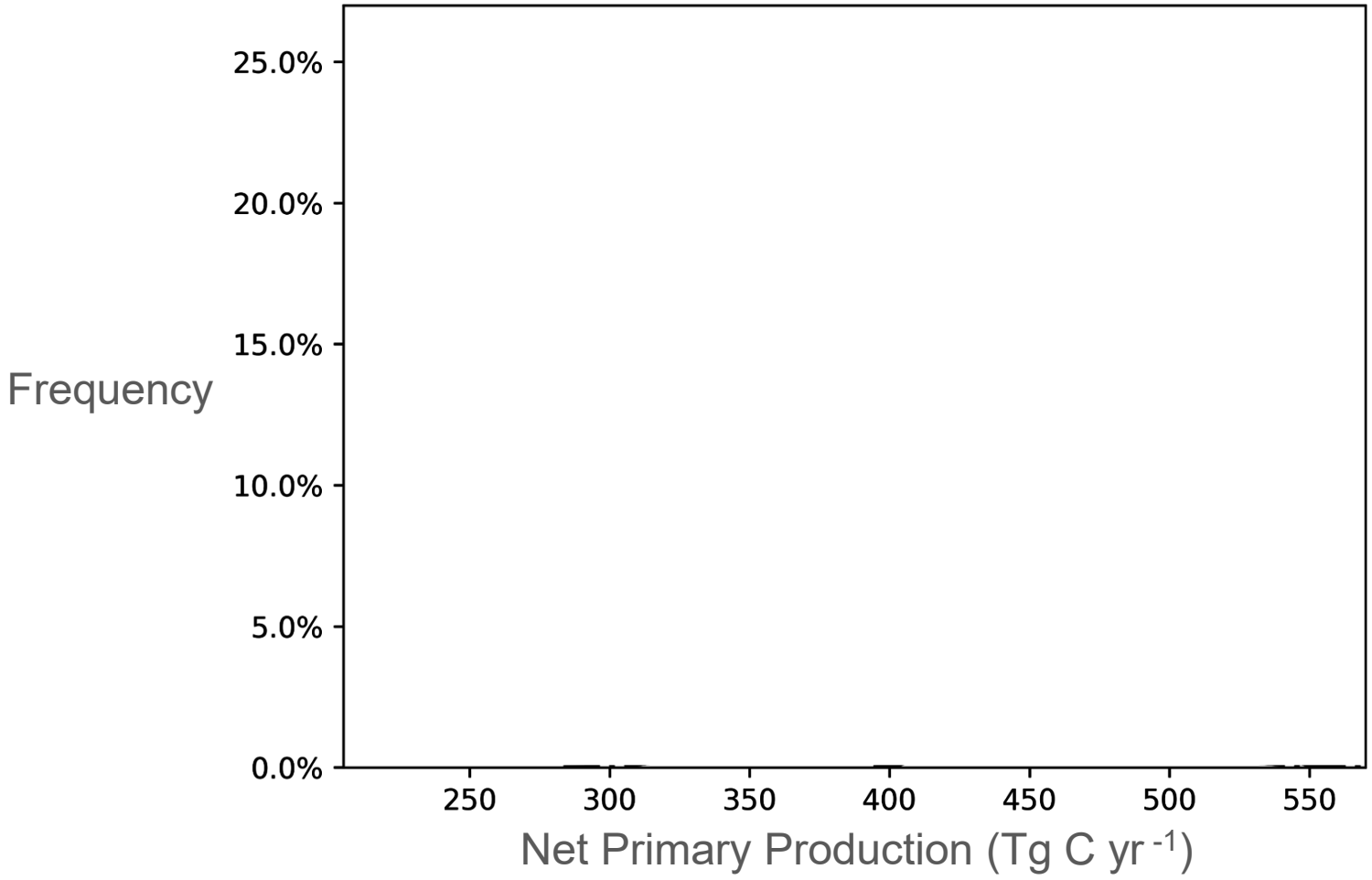
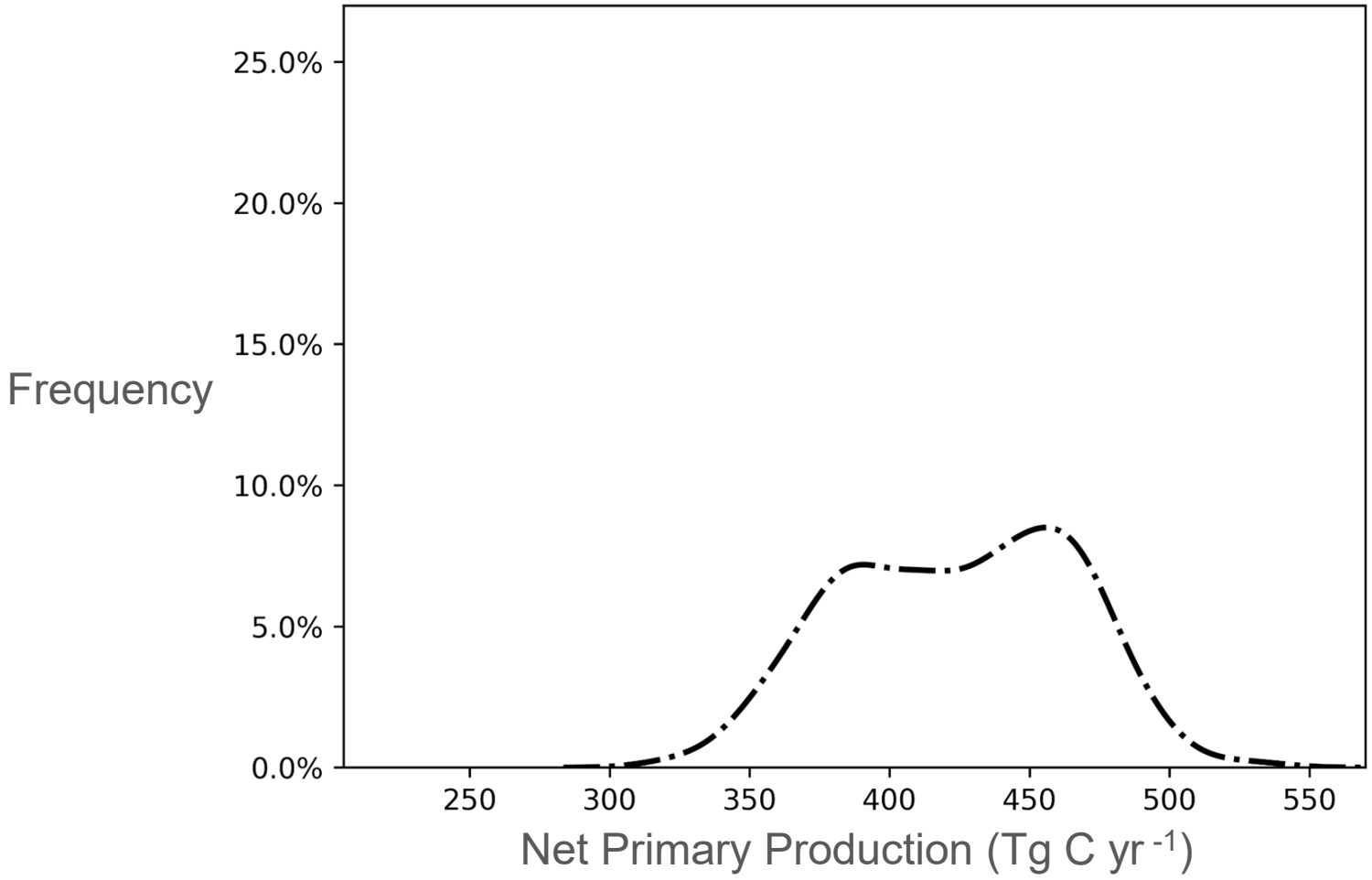


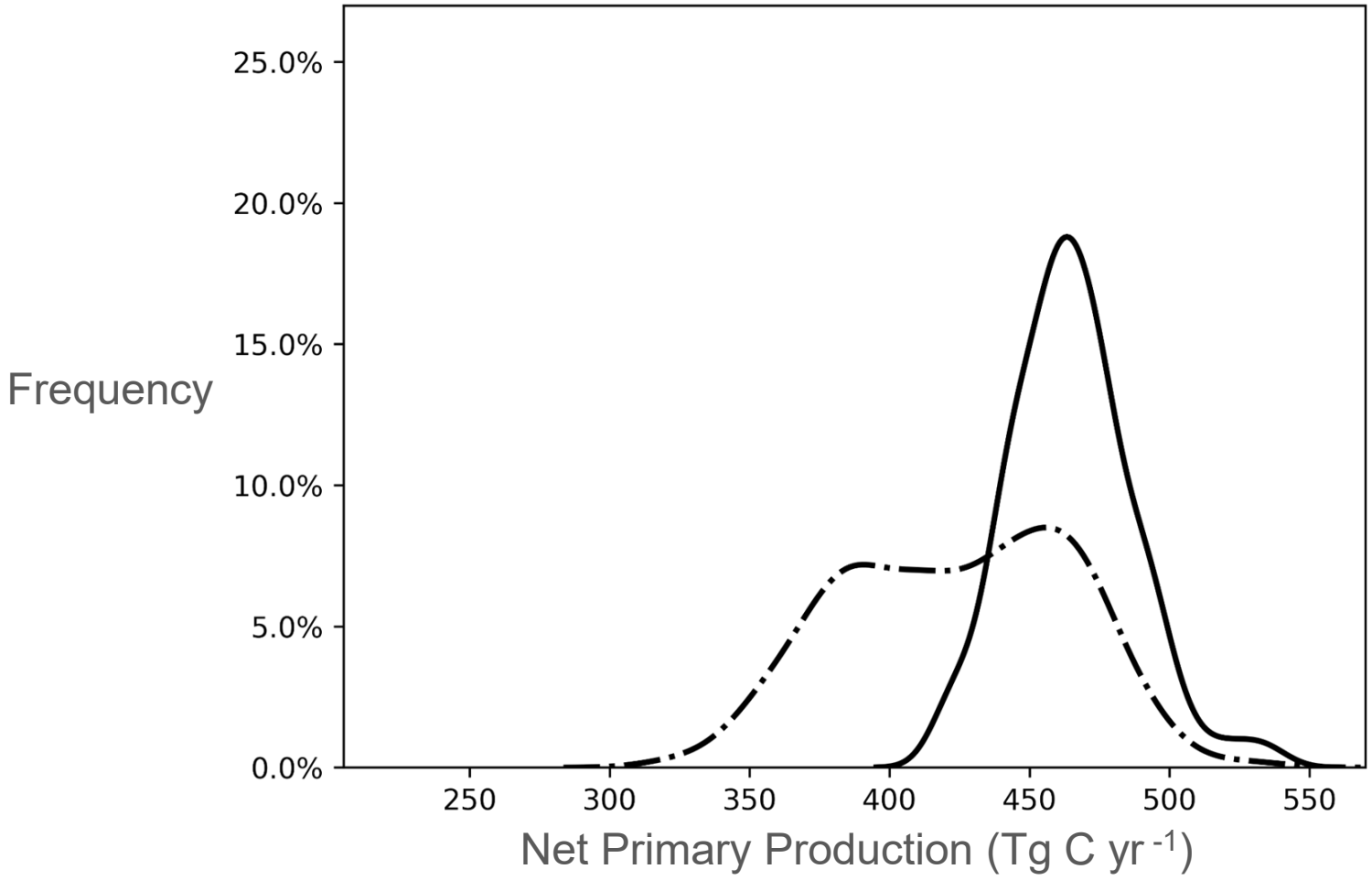
Figure Nicolaus et al., 2022

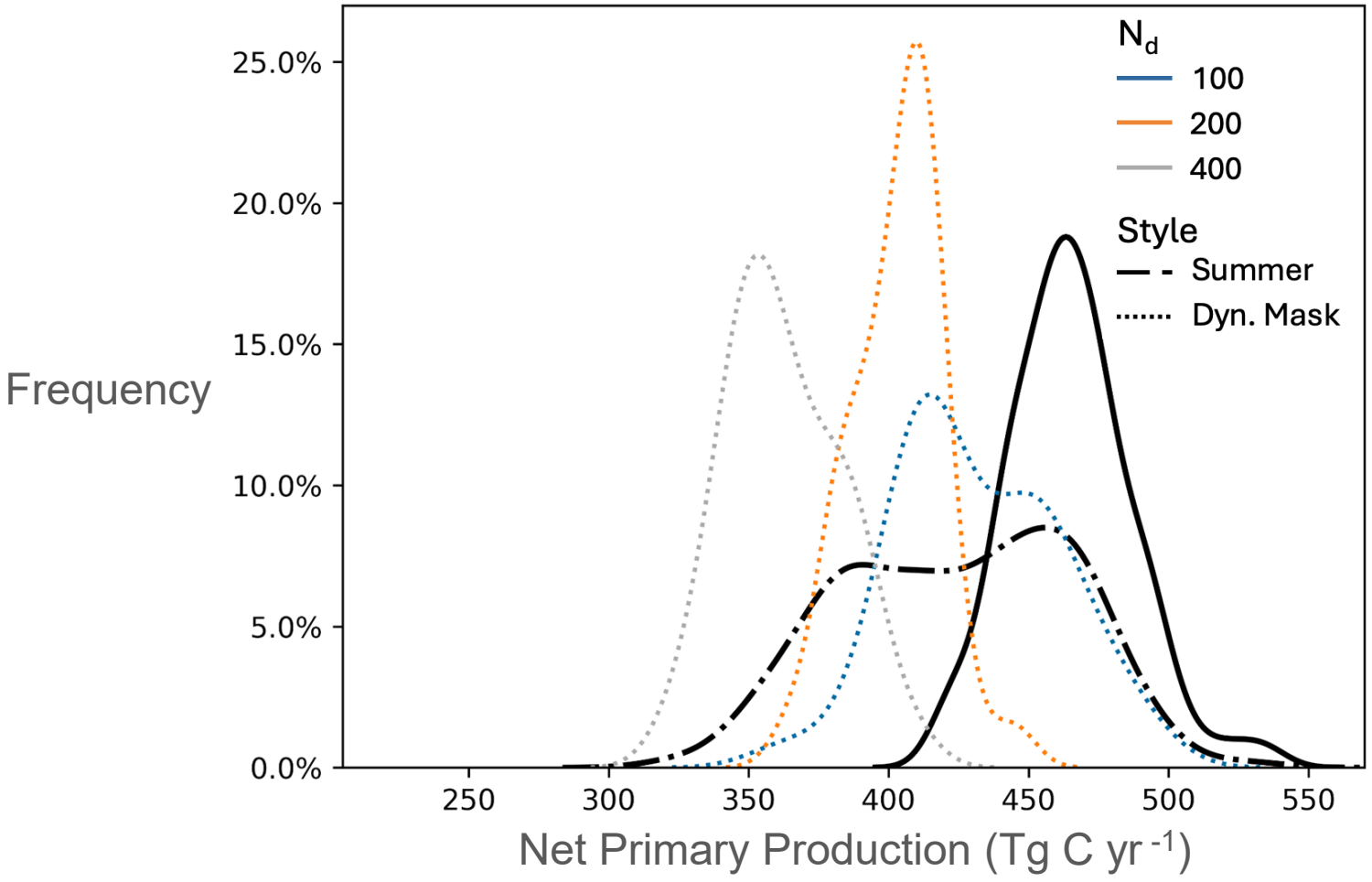
NOAA



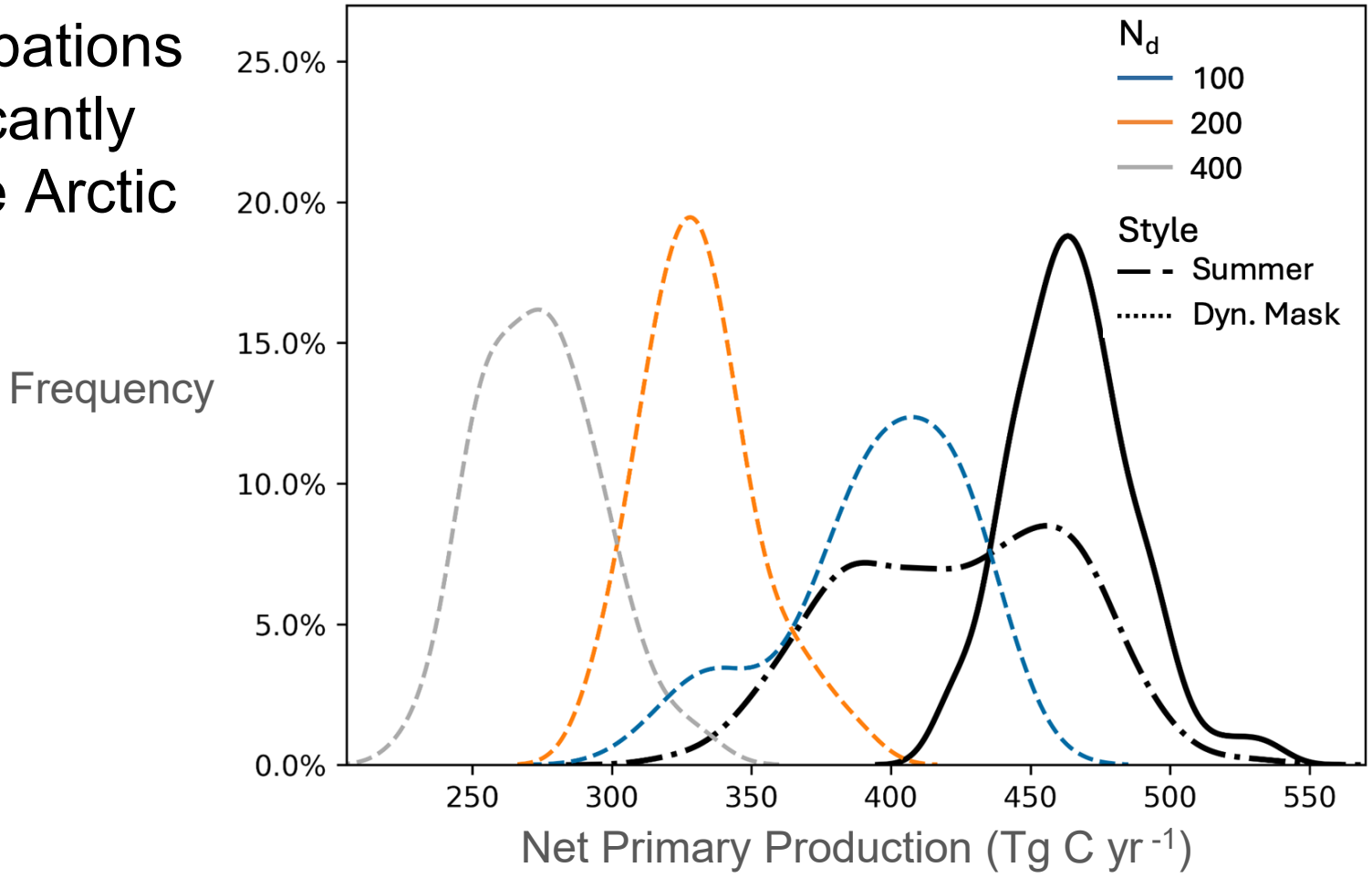

25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
Frequency
250
300
350
400
450
500
550
Net Primary Production (Tg C yr -1)


Frequency
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
250
300
350
400
450
500
550
Net Primary Production (Tg C yr -1)


Frequency
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
250
300
350
400
450
500
550
Net Primary Production (Tg C yr -1)

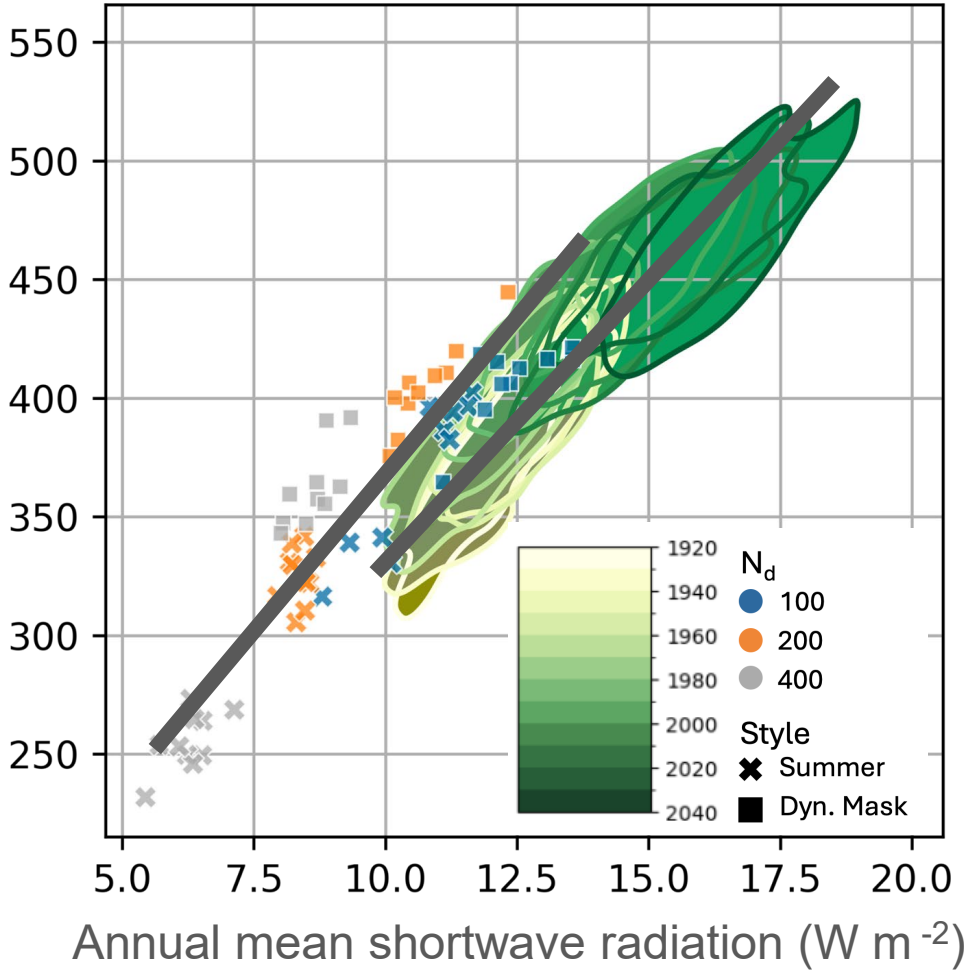

Frequency
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
250
300
350
400
450
500
550
Net Primary Production (Tg C yr -1)
N d
100
200
400
Style
Summer
Dyn. Mask

Perturbations significantly reduce Arctic NPP



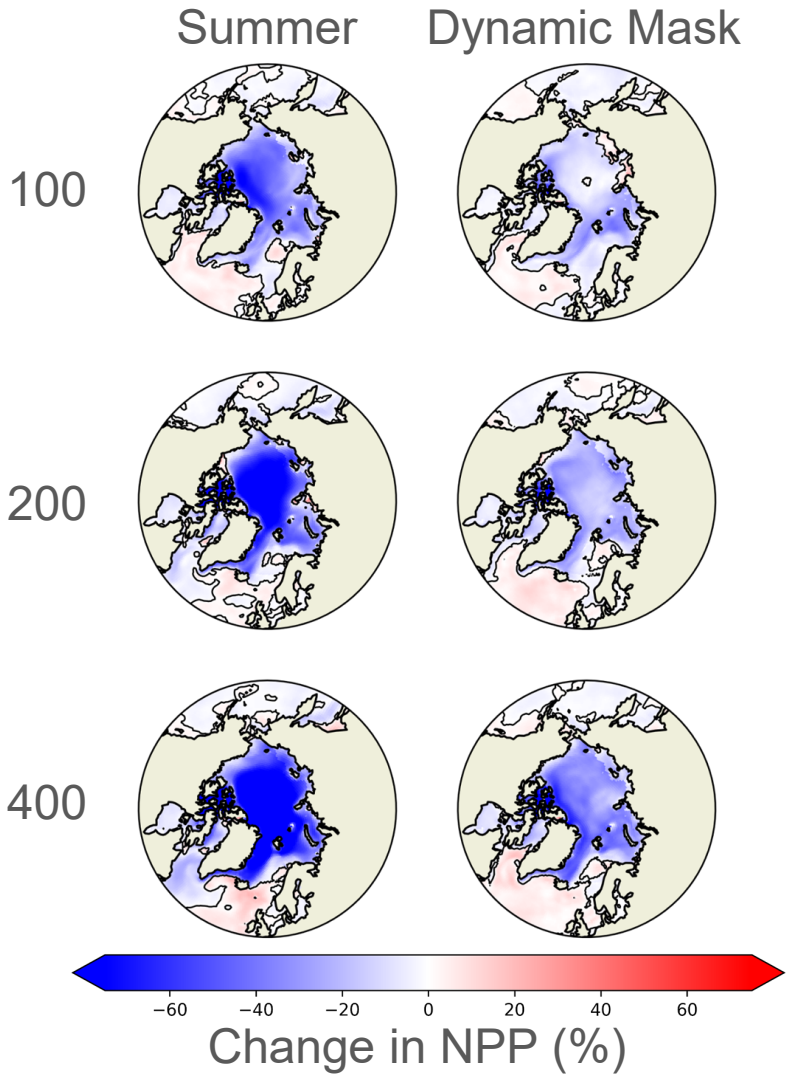
Lower light conditions drive reduced NPP

- Higher perturbed NPP at the same light level is likely due to changes in stratification



Decline is focused in the central Arctic

- 15 - 82% decline in NPP north of 80°N relative to unperturbed simulations
- 8 - 39% decline in NPP within the Arctic Circle (>67°N)
- 3 - 9% decline in NPP over the Arctic and sub-Arctic (>50°N)



Marine Ecosystem Impacts Takeaways

- Marine cloud brightening perturbations can substantially dampen Arctic and sub-Arctic phytoplankton productivity.
- Changes in productivity are largely tied to reductions in light driven by increased snow thickness, particularly in the Central Arctic.
- Reduced productivity likely impacts regional C sequestration and food availability to marine ecosystems

Key Takeaways

- Summer perturbations over marginal ice zone and ocean are most efficient
- Unprecedented climate states in the snow/sea ice, upper ocean, and marine ecosystem

Next Steps

- Other Arctic impacts (permafrost, Greenland Ice Sheet, etc.)
- Impacts outside Arctic (midlatitude temperatures, tropical precipitation, AMOC, etc.)
- Explore in CESM3 with updated cloud liquid and ice physics and melt pond physics