A wide-angle photograph of a vast, flat expanse of Arctic sea ice under a dramatic sky. The ice is broken into numerous irregular, polygonal floes of varying sizes, separated by dark, narrow channels of water. The sky transitions from a deep blue at the top to a bright yellow and orange near the horizon, where the sun is setting or rising. The overall scene is serene and expansive.

Reflecting Change:
Challenges and
Opportunities in measuring
and modeling Arctic surface
albedo

Patrick C. Taylor

NASA Langley Research Center

ARCSIX Operational Accomplishments

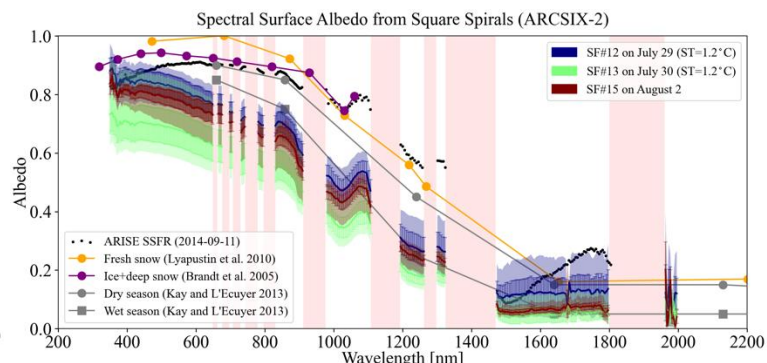
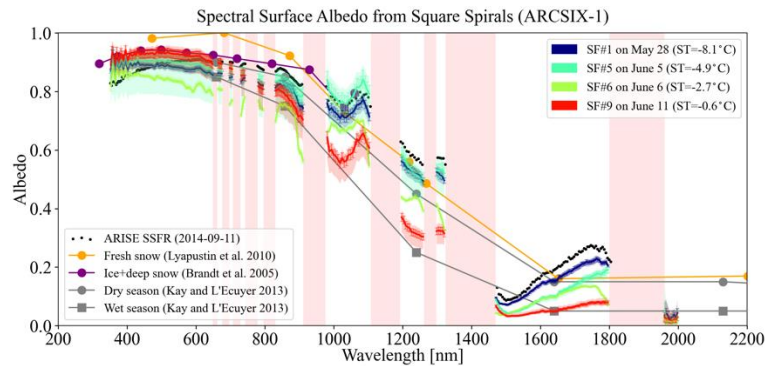
- 19 Wallops P-3 science flights accumulating 179.5 flight hours and traversing >47,000 miles
- 15 Langley G-III science flights accumulating 127 flight hours and traversing >52,000 miles
- 10 SPEC Learjet science flights accumulating >40 flight hours
- Brought together scientists from >22 different institutions both domestic and international
- Transported >75 QNCs into the Arctic: NASA C-130
- More than a dozen satellite coordination events
- Three aircraft coordination on 4 cloud walls.



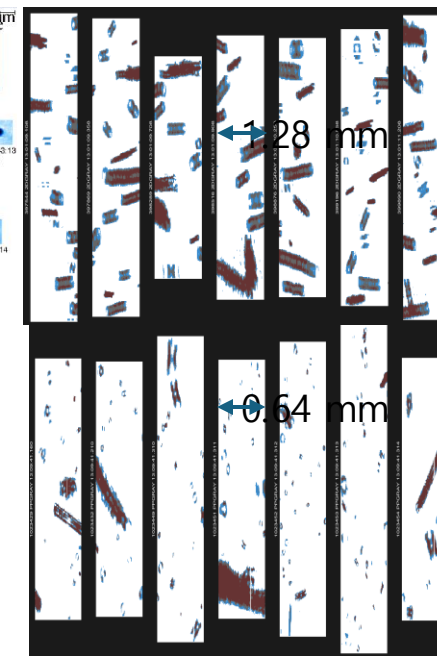
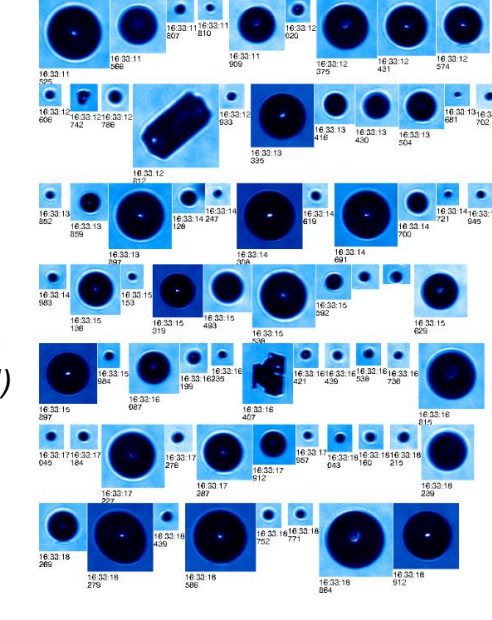
ARCSIX collected a first-of-its-kind data set that will be used to understand the drivers of Arctic climate decades.

ARCSIX Data Thumbnails

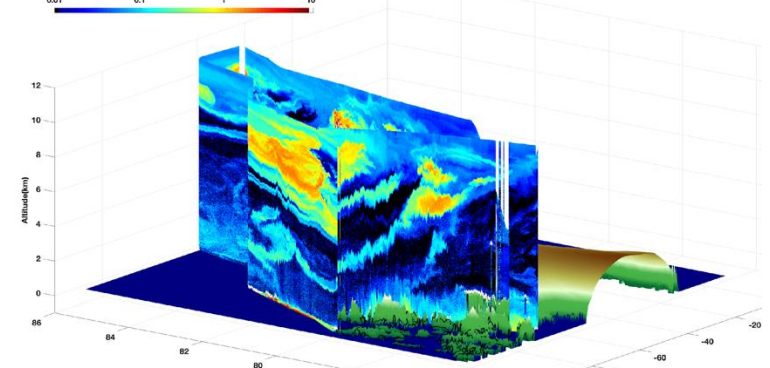
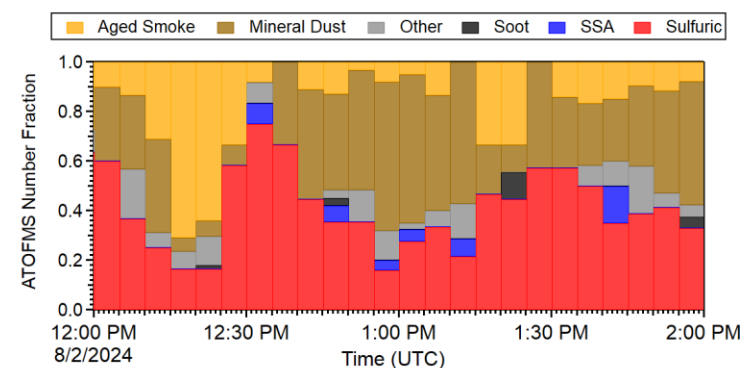
From: Alexei Korolev and SPEC team



5/28/2024.163311- focus at 20 and cutoff at 6
Version: 1.1.94 Time is not synced. Time is CPI's original time

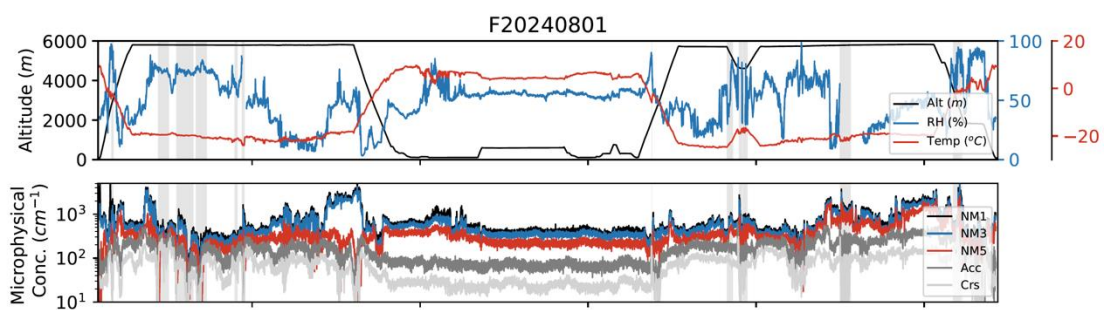


From SSFR Team: Sebastian Schmidt, Hong Chen, Ken Hirata, Arabella Chamberlain, Vikas Nataraja (CU)

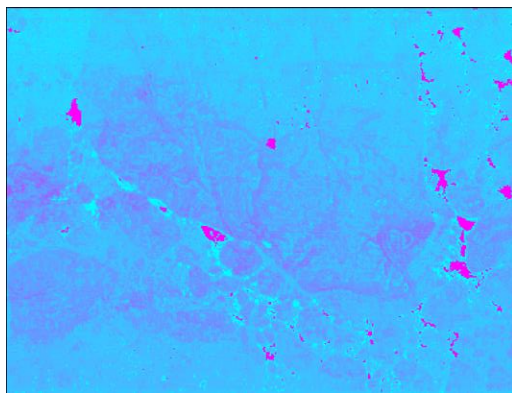
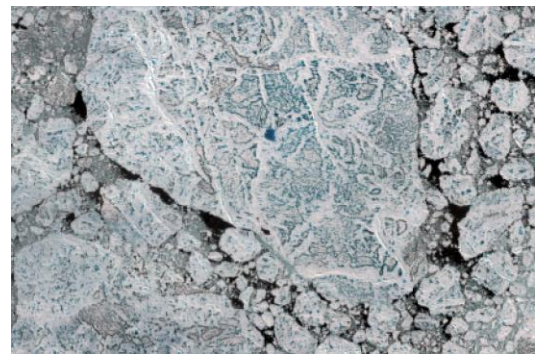


From: Niklas Bohn and AVIRIS team (JPL)

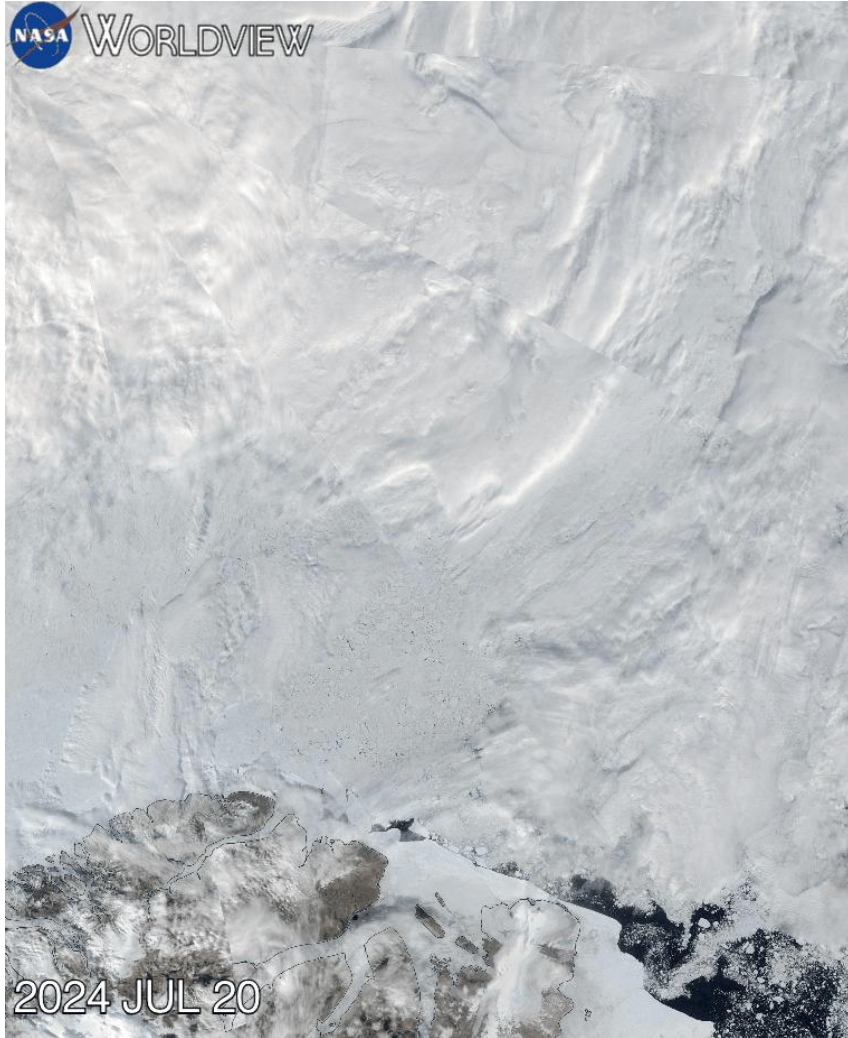
From the Pratt Group (U Mich.)



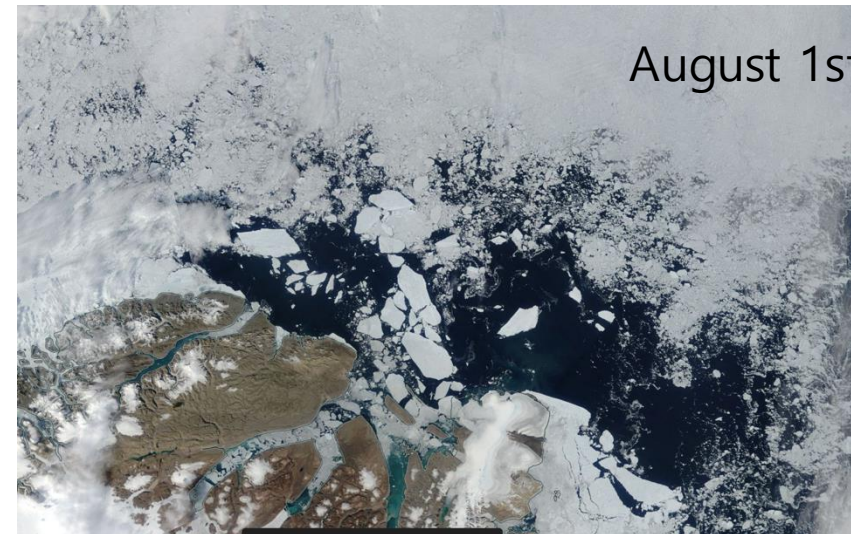
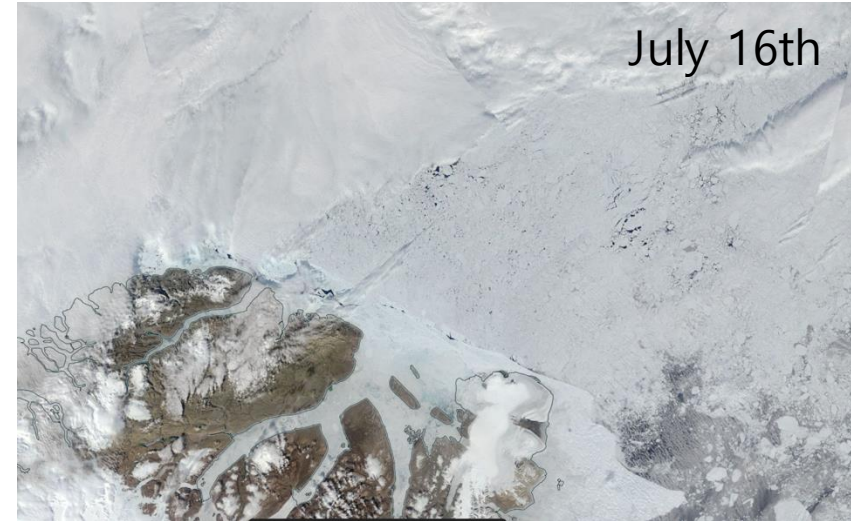
From: Matt Brown (Langley)



ARCSIX Accomplishments: What we saw



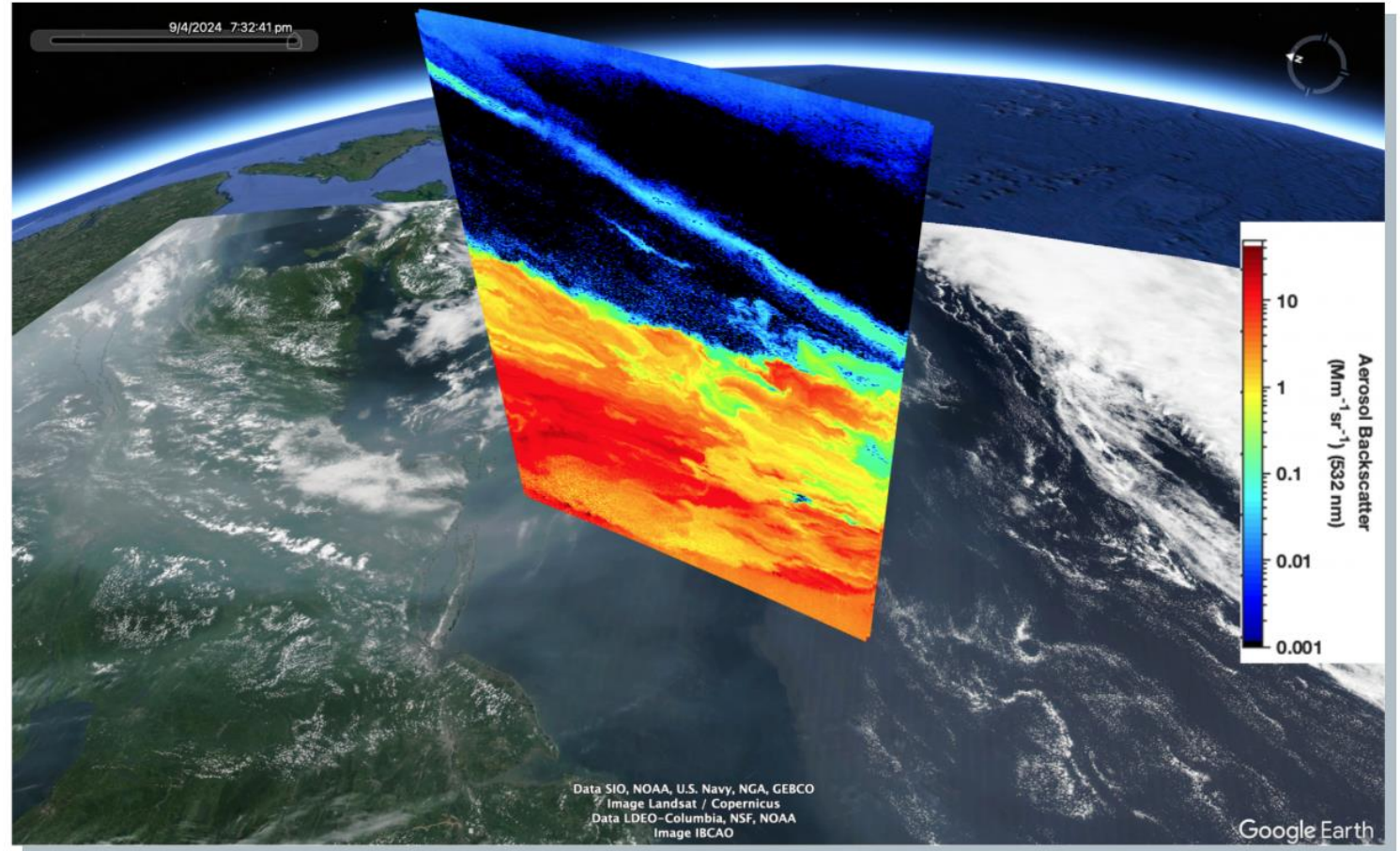
Arctic sea
ice anomaly



ARCSIX collected a first-of-its-kind data set that will be used to understand the drivers of Arctic climate decades.

EarthCARE underflight: 8/16

- We accomplished a coordinated EarthCARE underflight.
- The flight track traversed a large plume from the Canadian wildfires.
- Launched three dropsondes around the time of the overpass to provide atmospheric temperature and water vapor.



Aerosol backscatter over the North American Atlantic coast. (NASA Langley Research Center/HALO)

From: Amin Nehrir





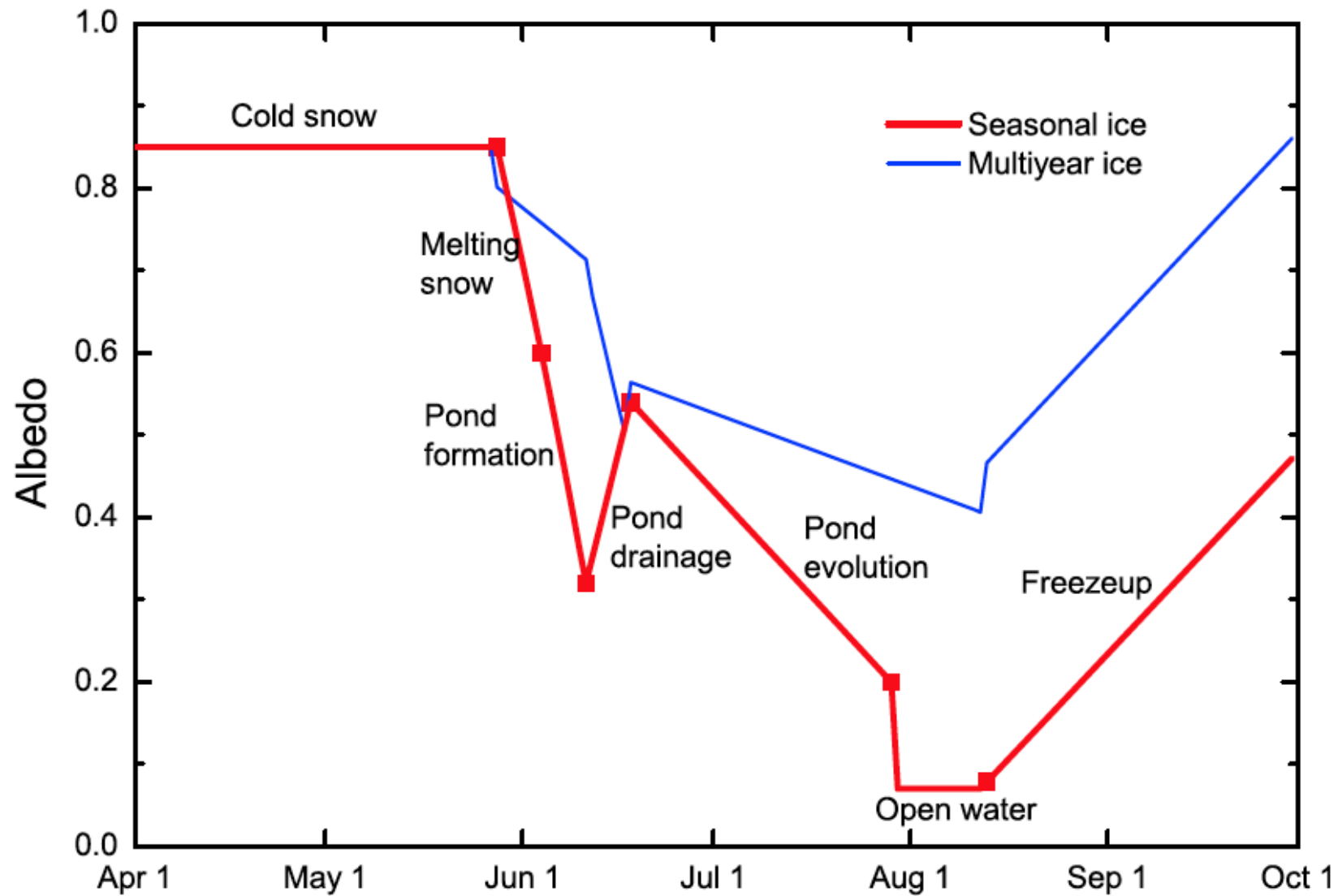
Key Takeaways:

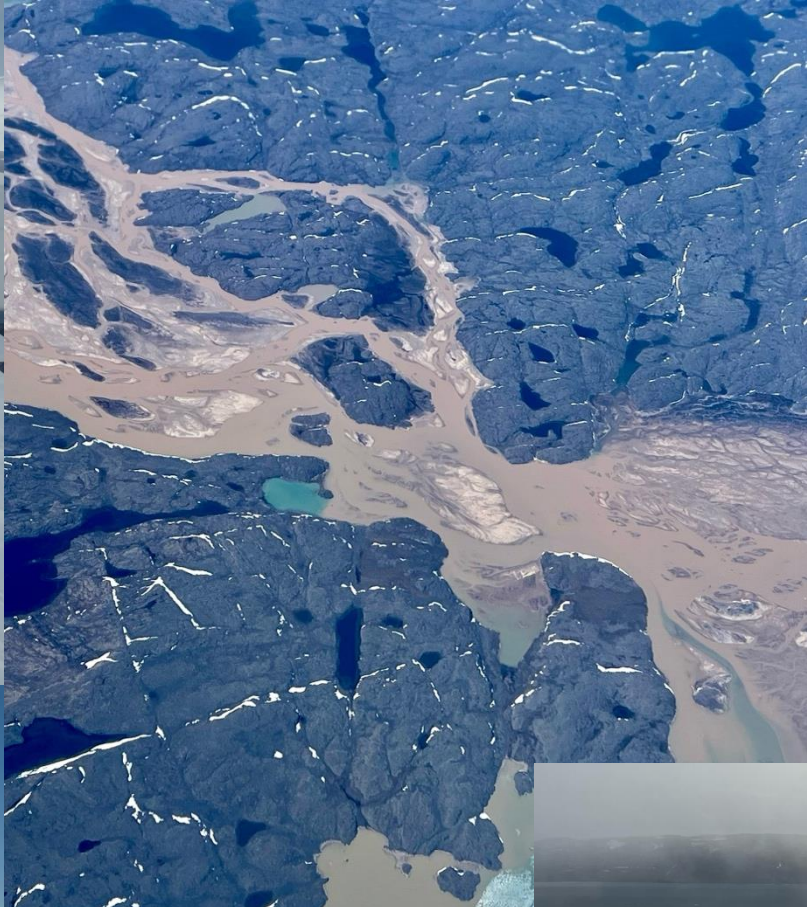
- **Arctic surface albedo remains a key source of uncertainty** in climate models for both present-day and projections of future change.
- **Projections of future Arctic warming are likely underestimated** based upon the current set of
- **Interactions between sea ice and the atmosphere are still missing in current climate model simulations.**
- We need an **focused, collective effort (Taskforce)** joint between model developers, observationalists, and diagnosticians **to address these discrepancies in polar surface albedo** between models and observations.

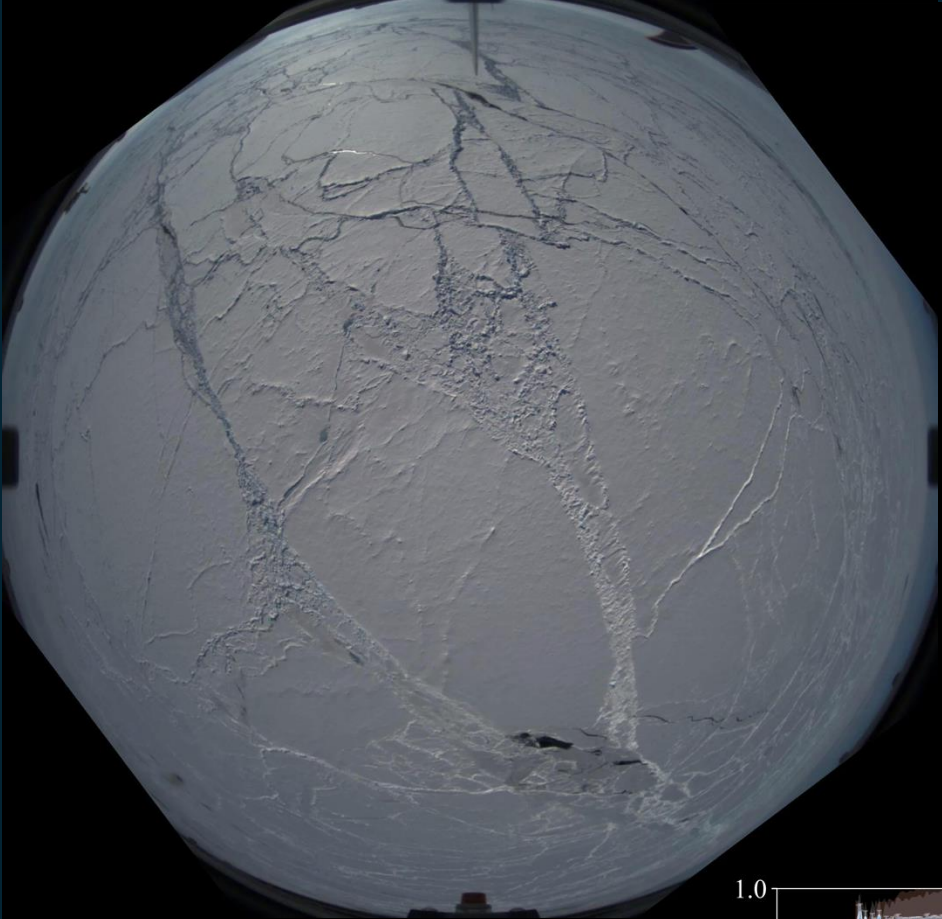
What is the seasonal variation in Arctic sea ice surface albedo?



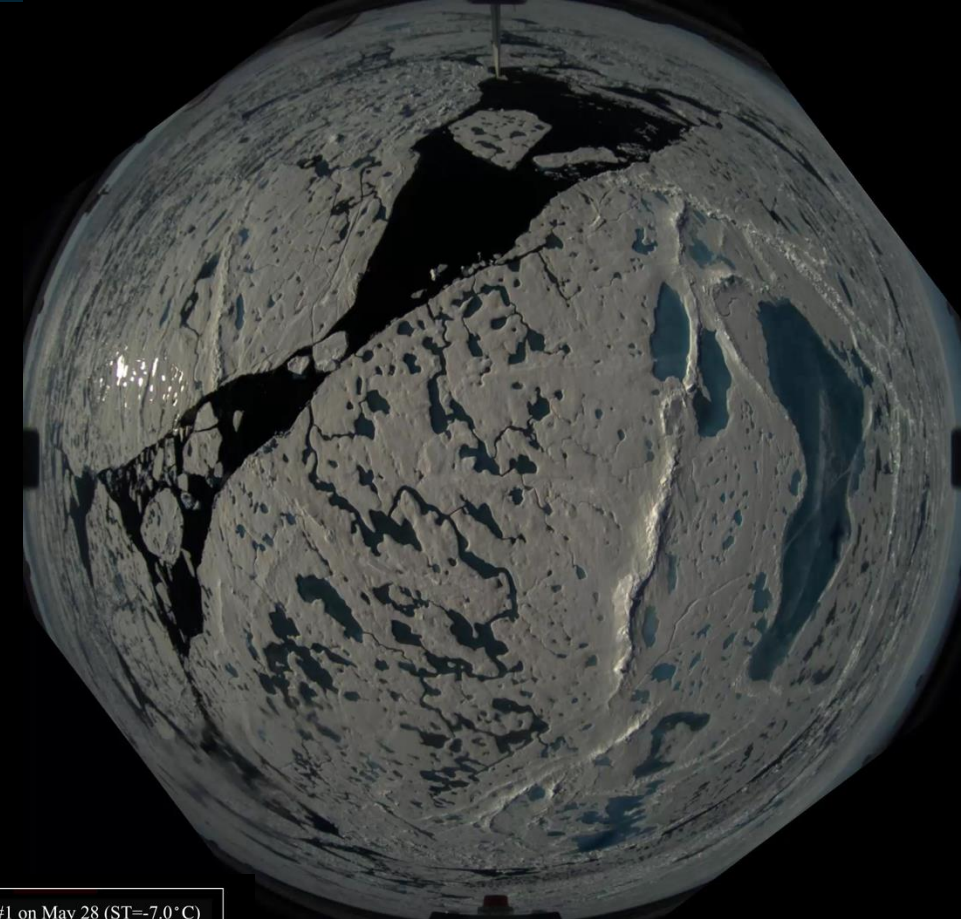
Variations in Arctic sea ice surface albedo



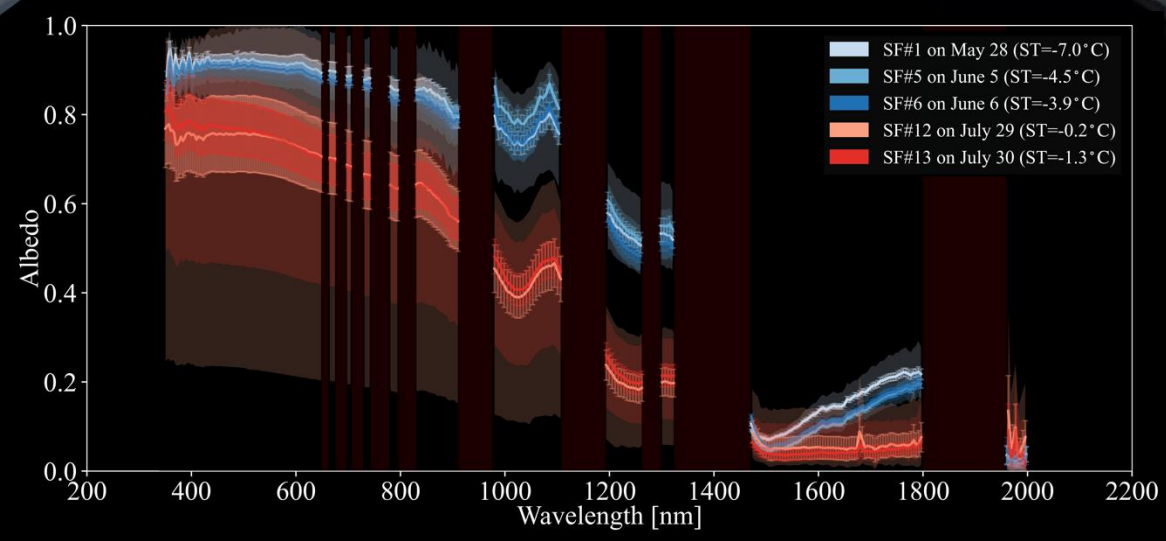




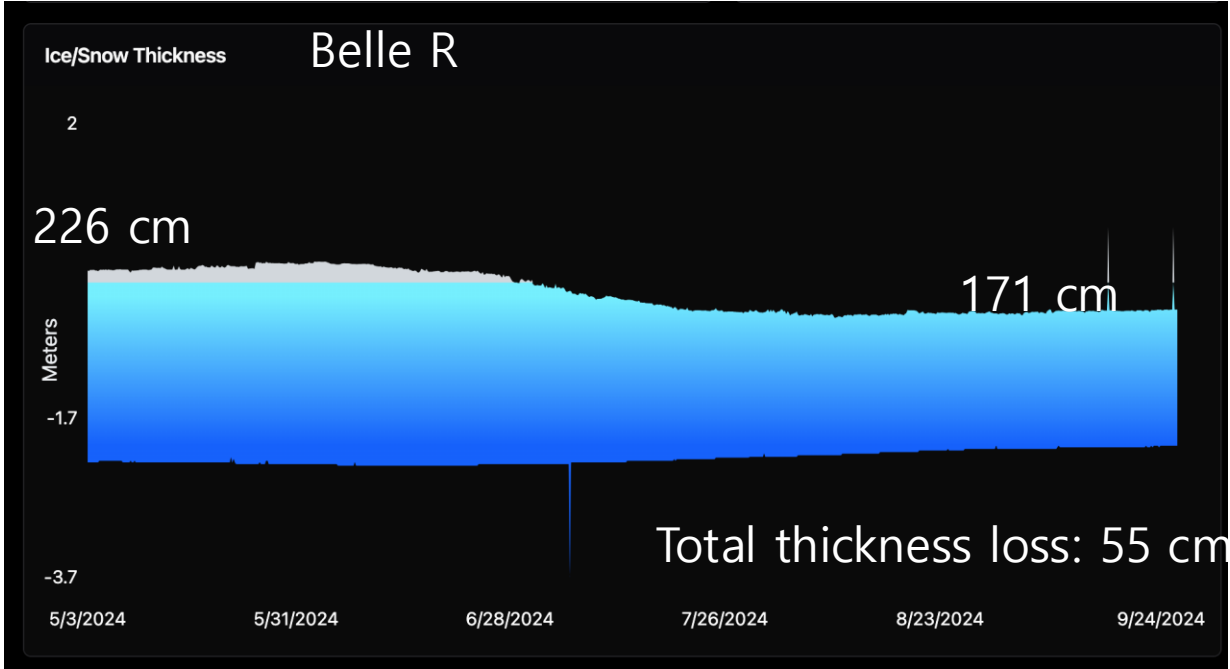
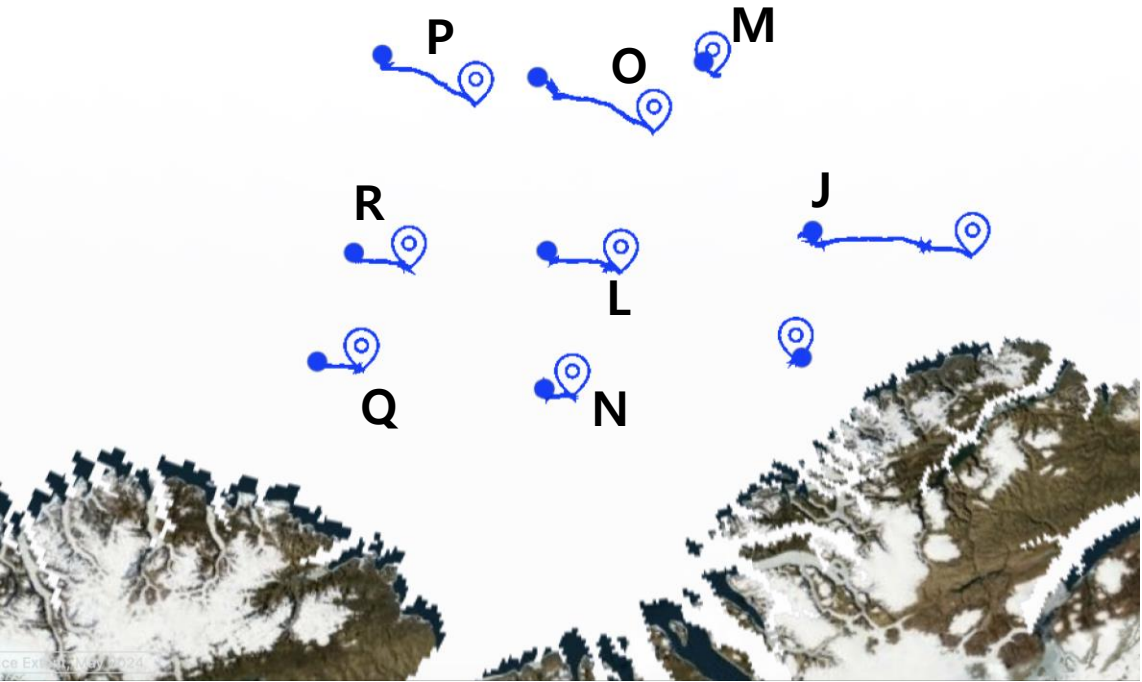
Spring: SF #1 May 28, 2024



Summer: SF# 13 July 30, 2024



Sea ice mass balance buoys: Belle Array



The Belle sea ice buoy array provides:

- Ground data of sea ice and atmospheric properties
- Enables the connection between the spring and summer campaign

Can view buoy data at:
<https://www.cryosphereinnovation.com>



The Arctic surface rapidly evolves and is complex...

Early summer



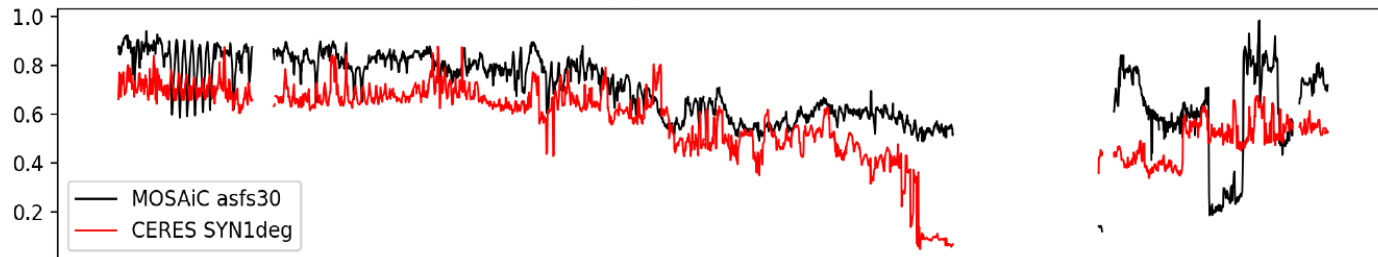
Late summer



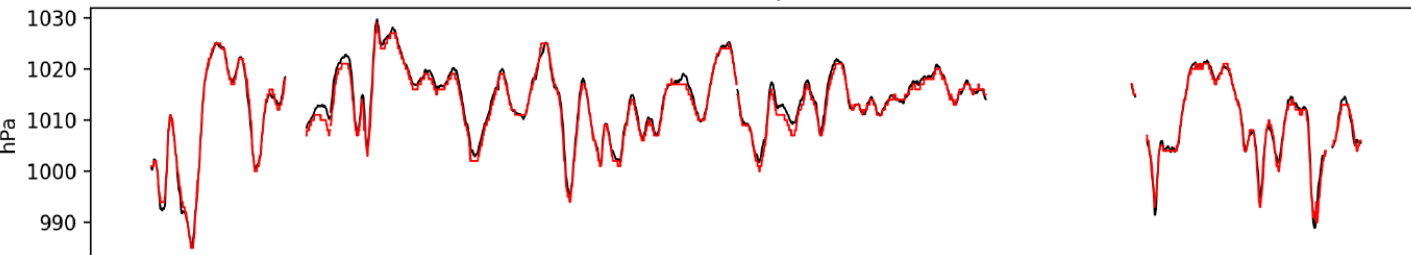
ARCSIX will observe the full sea ice albedo evolution

Meteorological conditions: MOSAiC and CERES SYN1deg

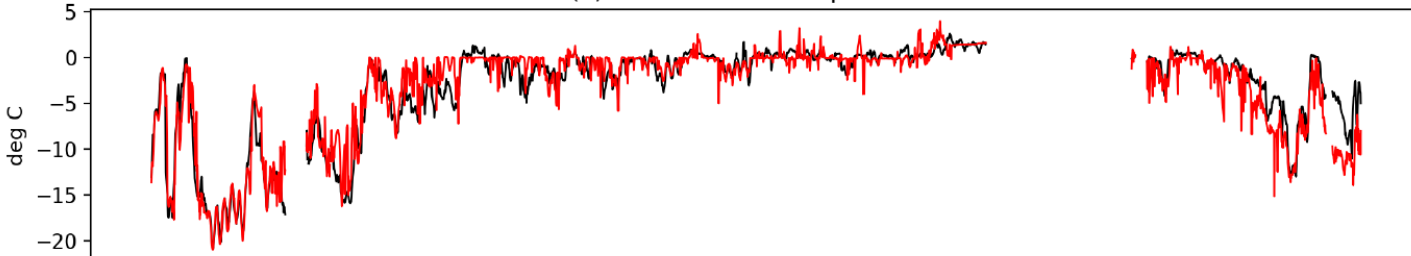
(a) Surface albedo



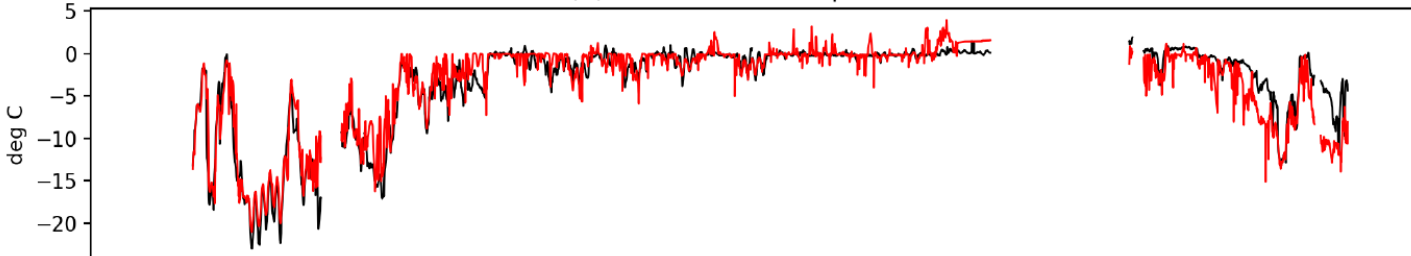
(b) Surface pressure



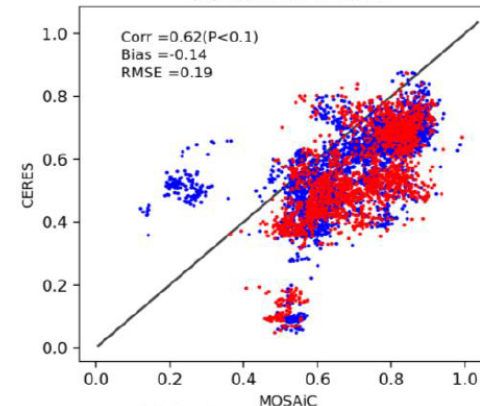
(c) Surface skin temperature



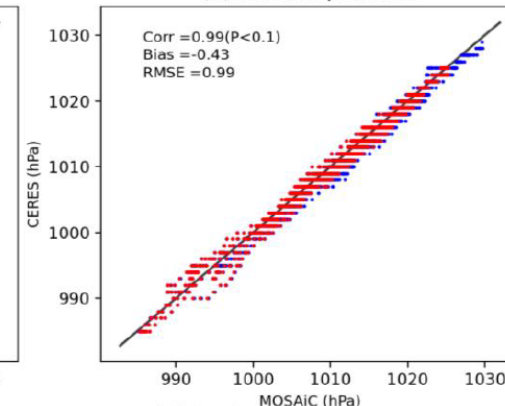
(d) Surface skin temperature



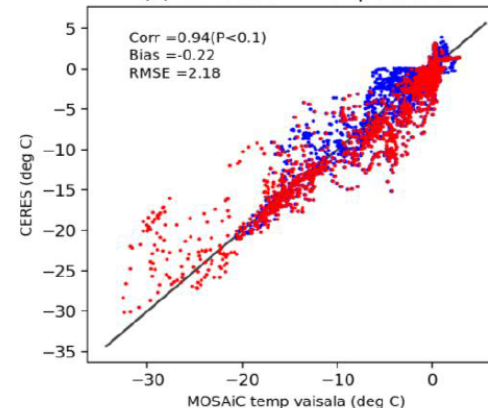
(a) Surface albedo



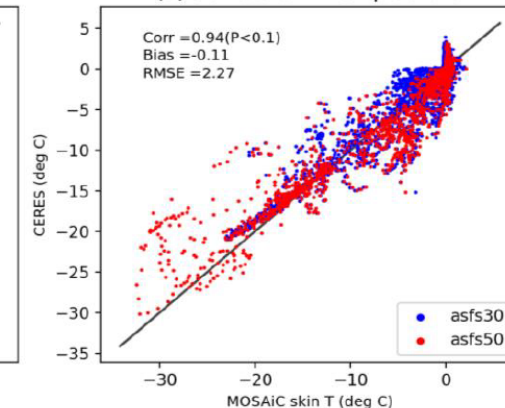
(b) Surface pressure



(c) Surface skin temperature

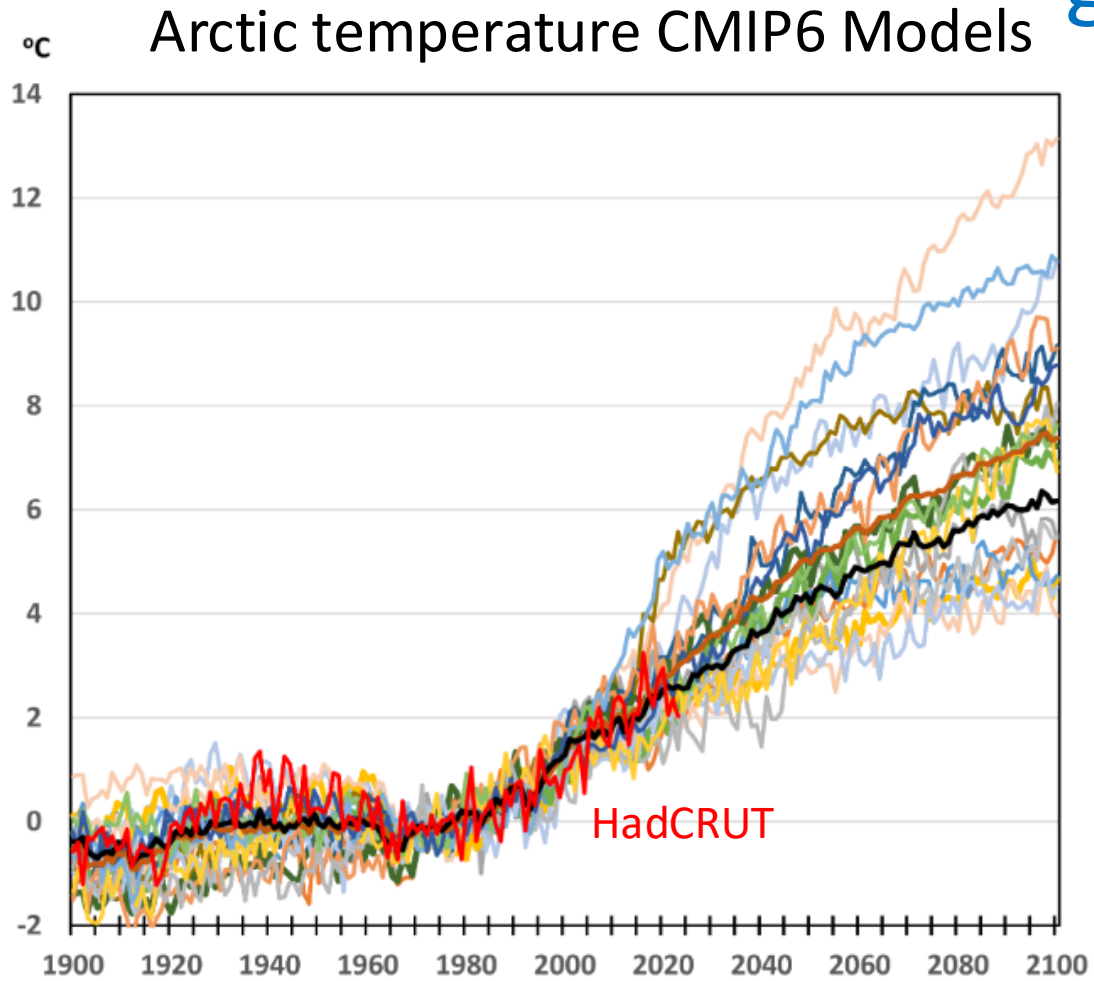


(d) Surface skin temperature



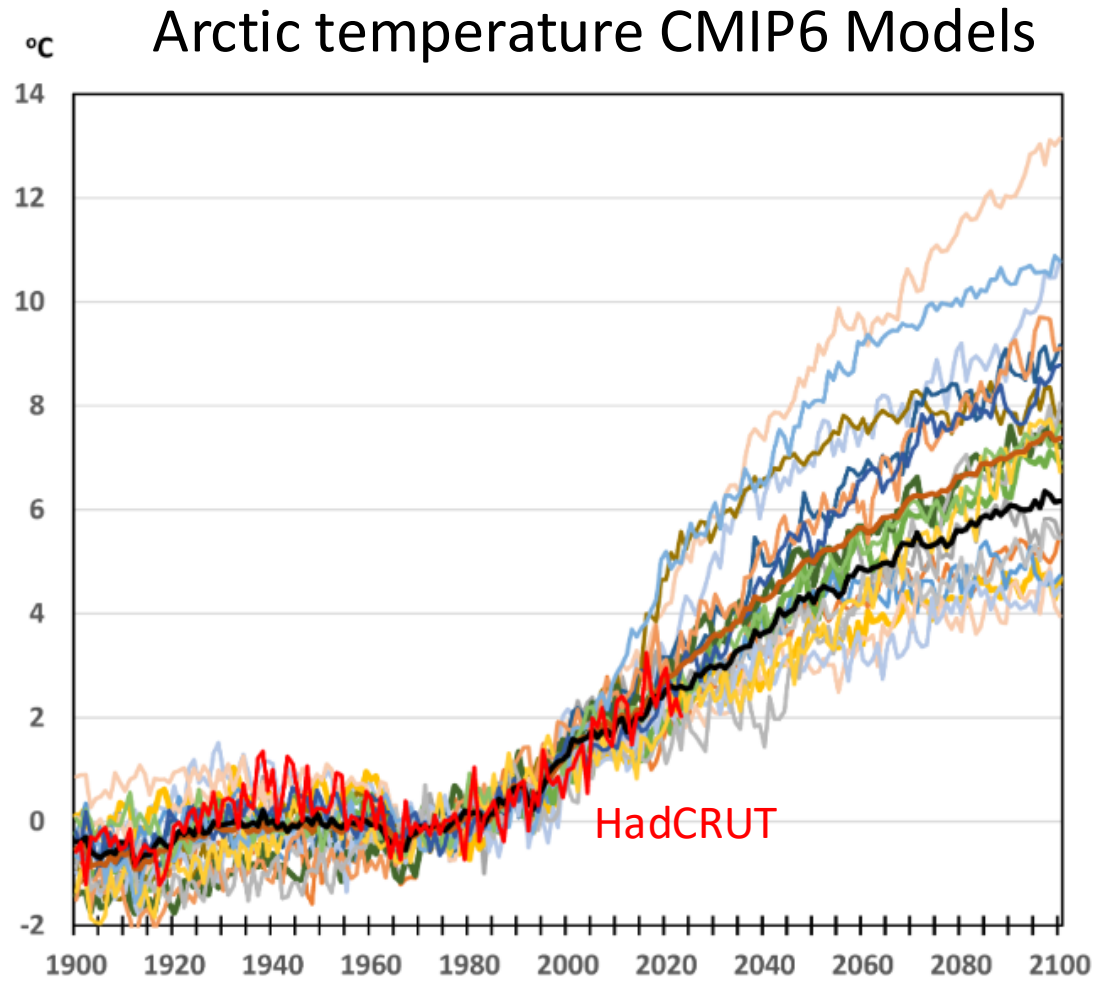
- The SYN1deg constantly underestimates the surface albedo during summertime
- Large uncertainty remains in surface skin temperature when it reaches melting point ($\sim 0^{\circ}\text{C}$)

The Arctic is warming nearly four times faster than the globe

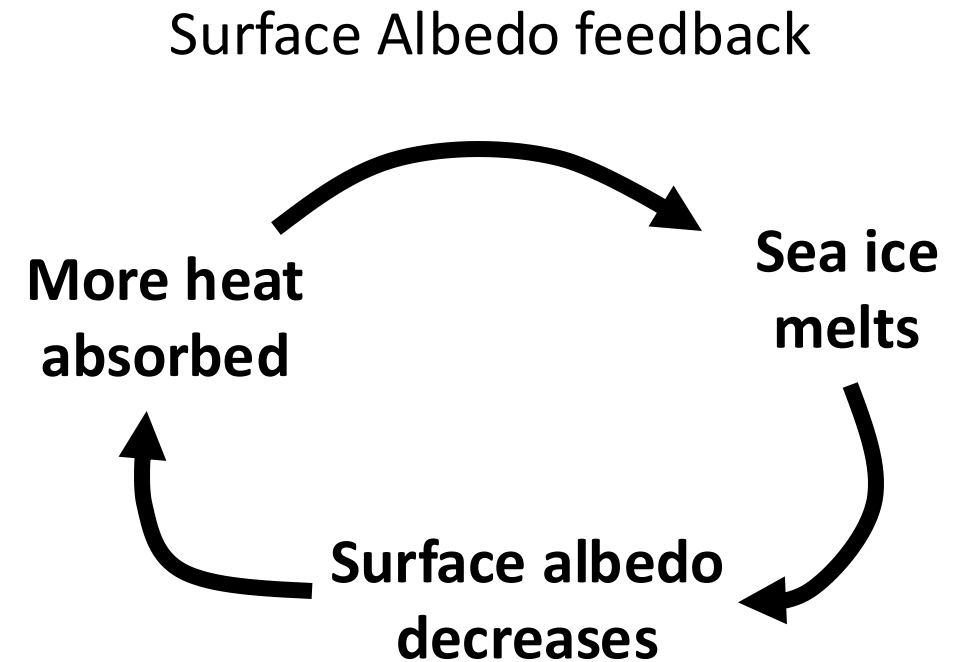


Chylek et al. 2024

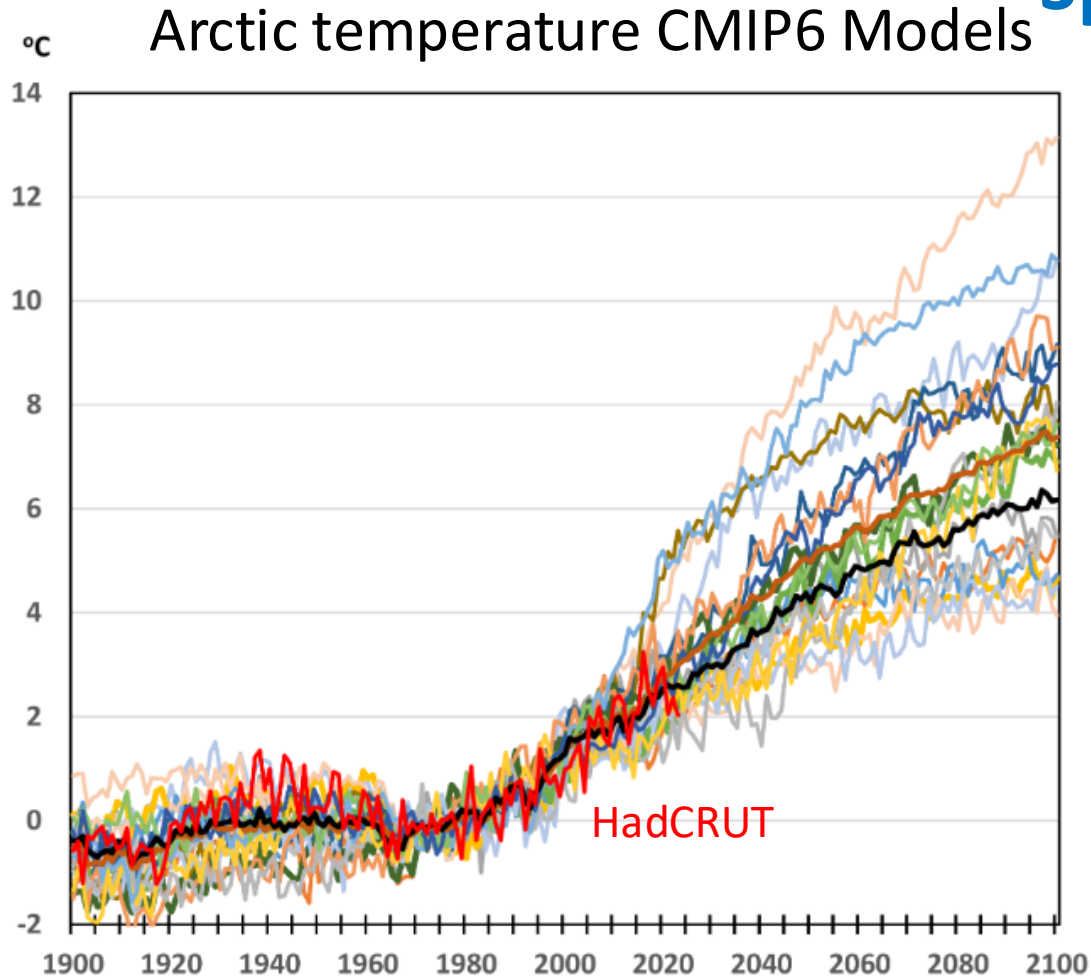
The surface ice-albedo feedback is widely accepted to play a leading role on Arctic warming



Chylek et al. 2024

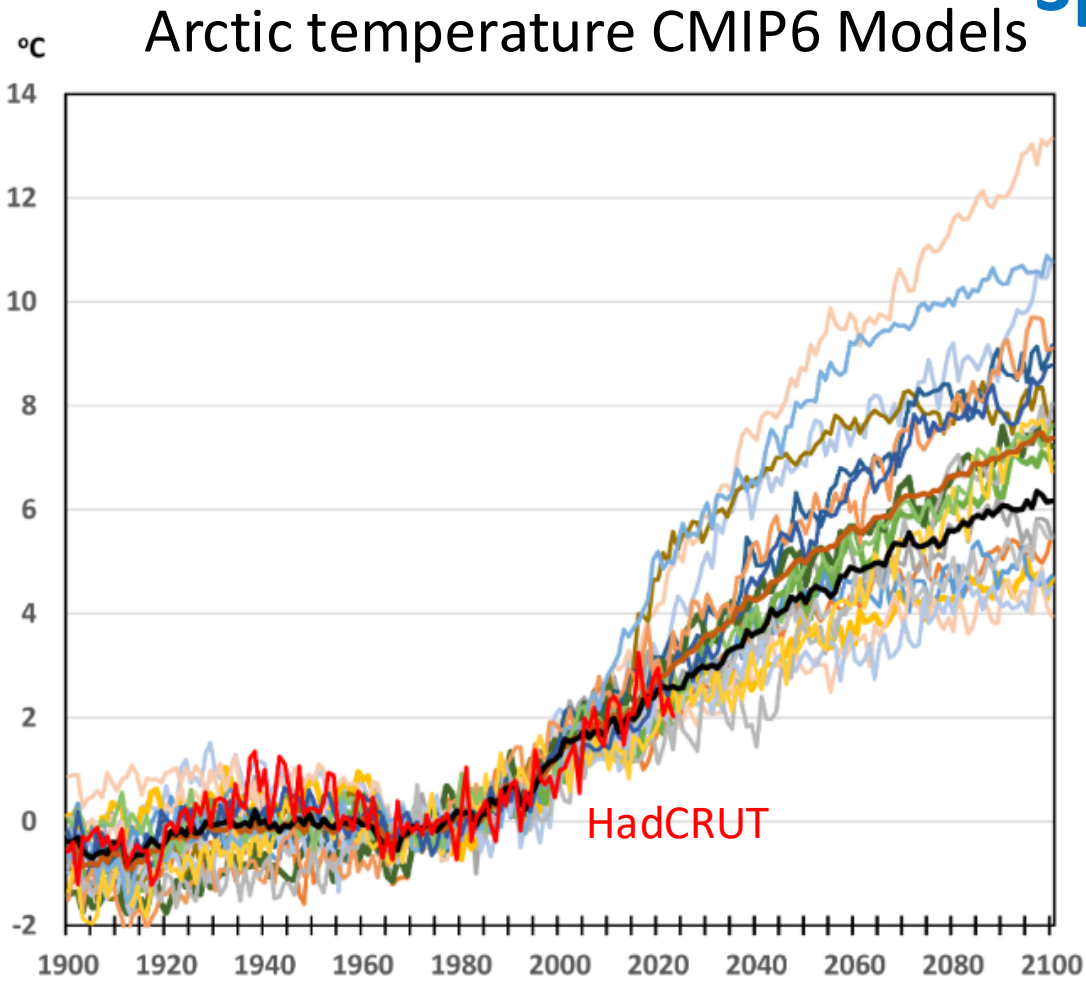


The albedo feedback contributes most to inter-model spread



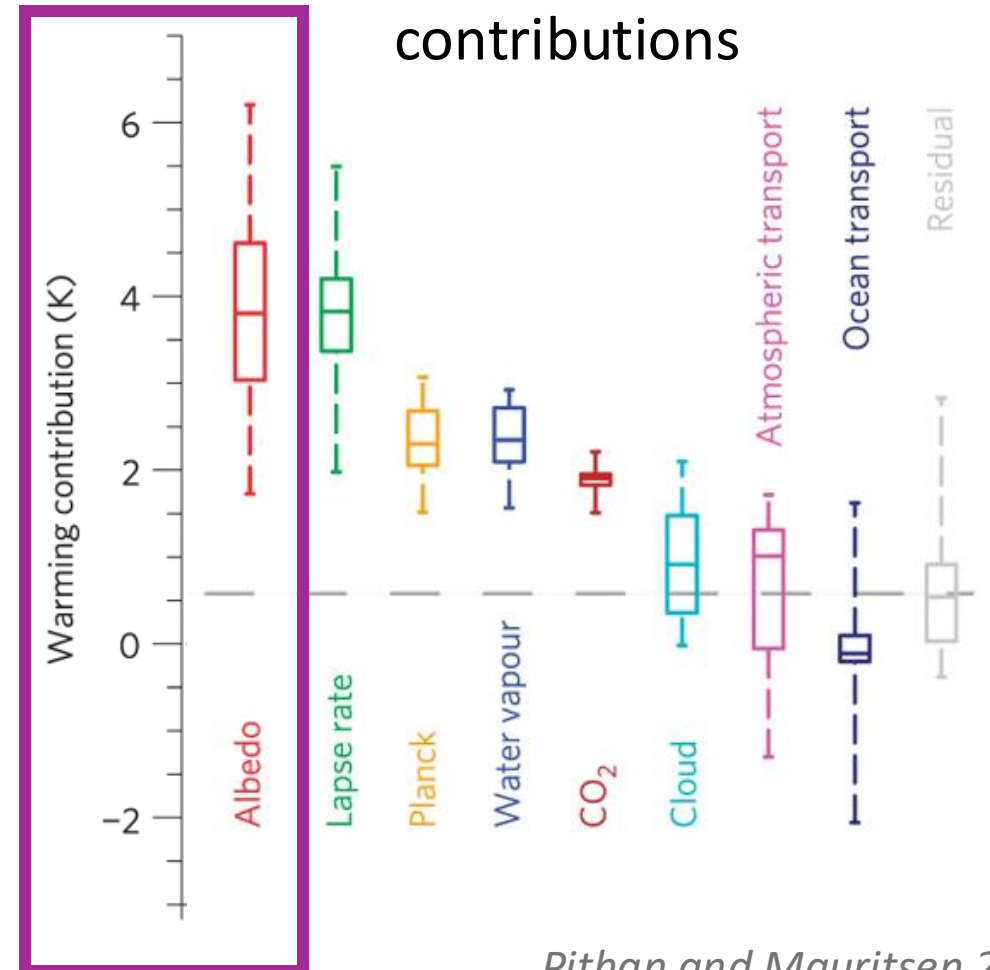
Chylek et al. 2024

The albedo feedback contributes most to inter-model spread



Chylek et al. 2024

Inter-model spread of polar warming contributions



Pithan and Mauritsen 2014

A comparison of CERES Surface albedo in the Arctic with AMIP and CMIP6 model output

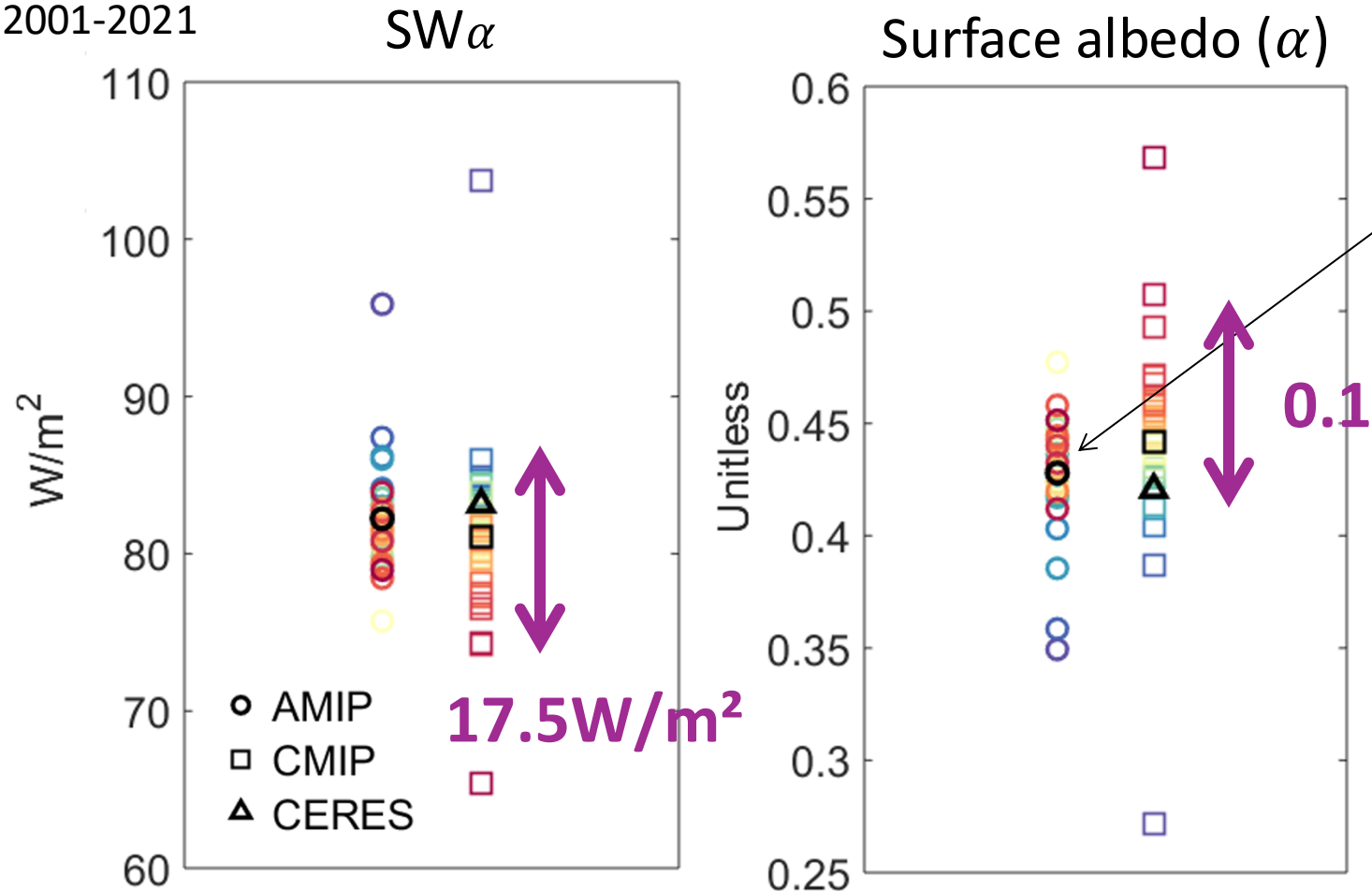
- CERES EBAF Ed4.1 product : 2001-2021
- AMIP 32 models: historical run, 1980-2014 (SST & SIC fixed)
- CMIP 32 models: historical run, SSP245/585 1980-2100 (Full coupled models)
- Hurrell SST/sea ice consistency criteria applied to merged HadISST & NCEP-012
- ERA5 reanalysis: 1980-2021

$$\text{Surface albedo : } \alpha_s = \frac{F_{\uparrow}^{SFC}}{F_{\downarrow}^{SFC}}$$

averaged over 65°N,
sunlight season (Mar through Sep)

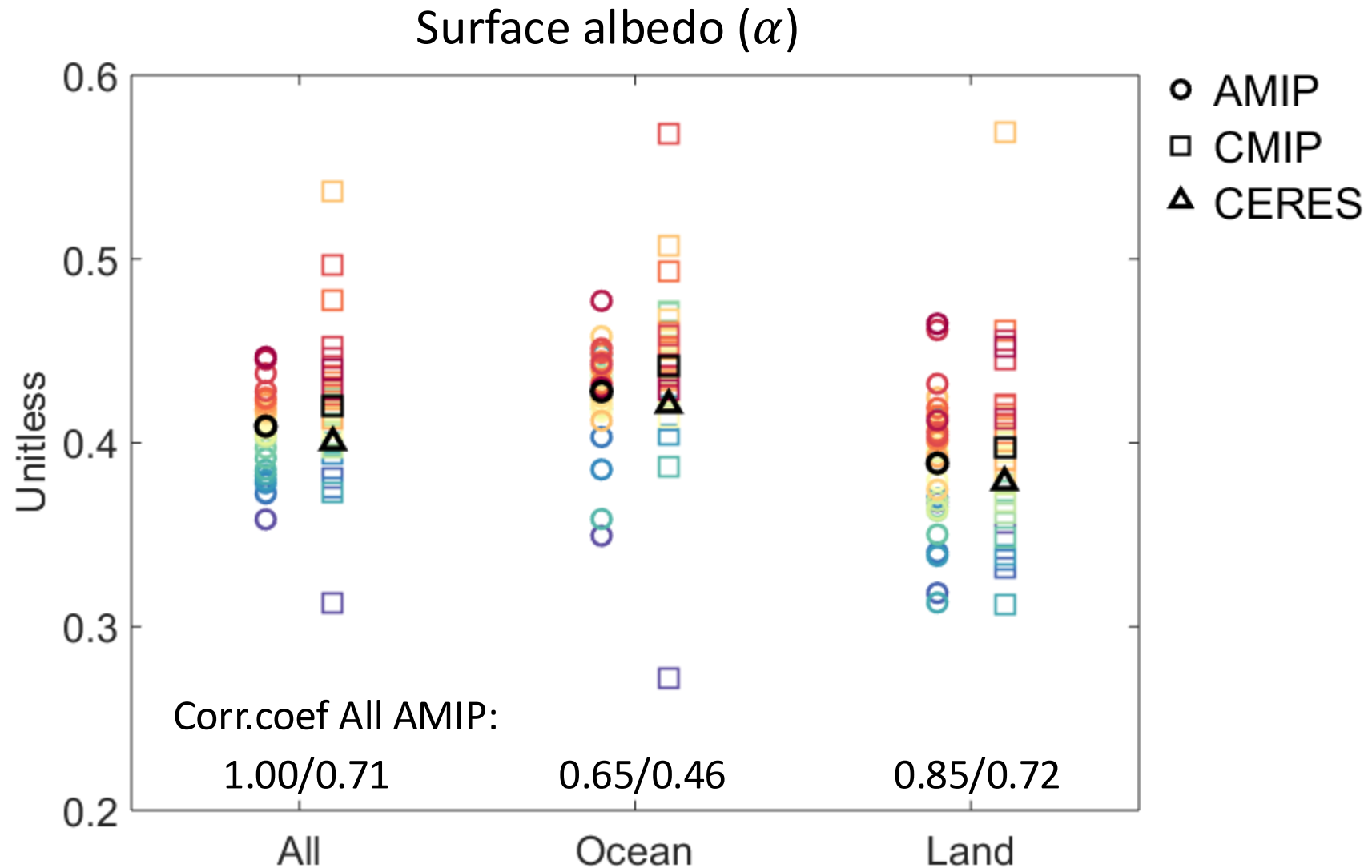
Surface Albedo differences significantly impact Arctic surface SW radiation budget

*Present-day: 2001-2021

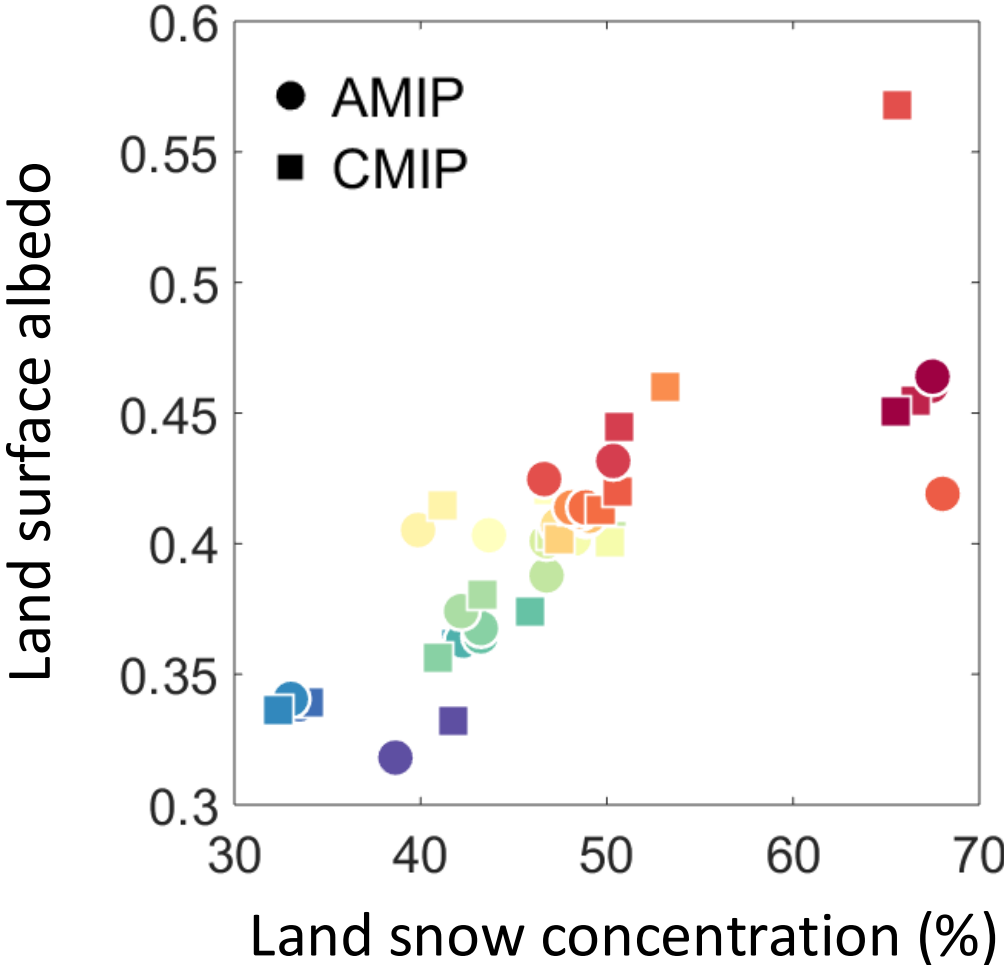


AMIP: prescribed SST & sea ice concentration

Most inter-model spreads in CMIP models are originated from AMIP simulations



Models with a larger land snow concentration exhibit the higher surface albedo

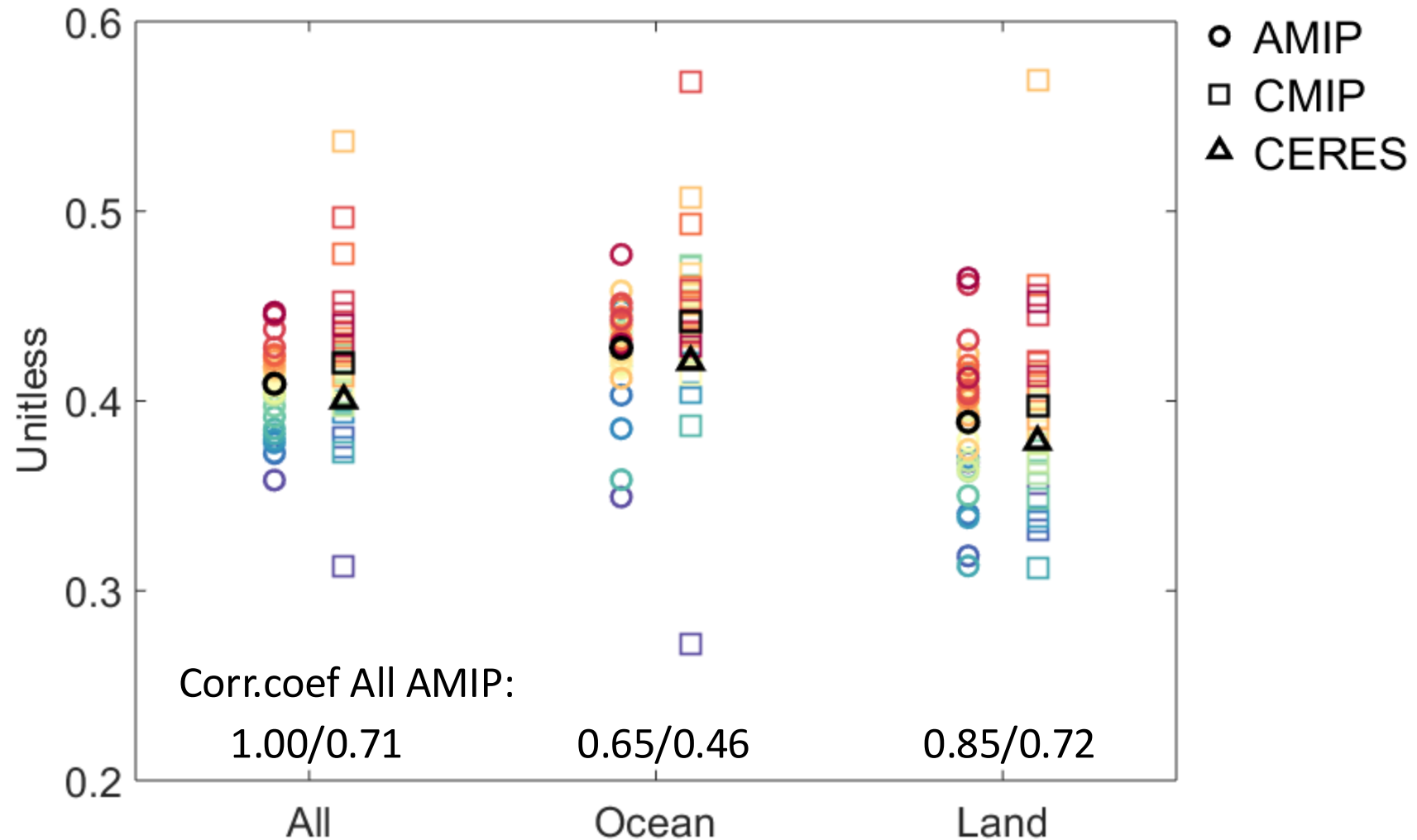


Correlations

land snow & land albedo	0.82 (AMIP) 0.85 (CMIP)
land albedo AMIP& CMIP	0.80
land snow AMIP&CMIP	0.80

Sea ice concentration is not a main driver for spreads in surface albedo?

Surface albedo (α)

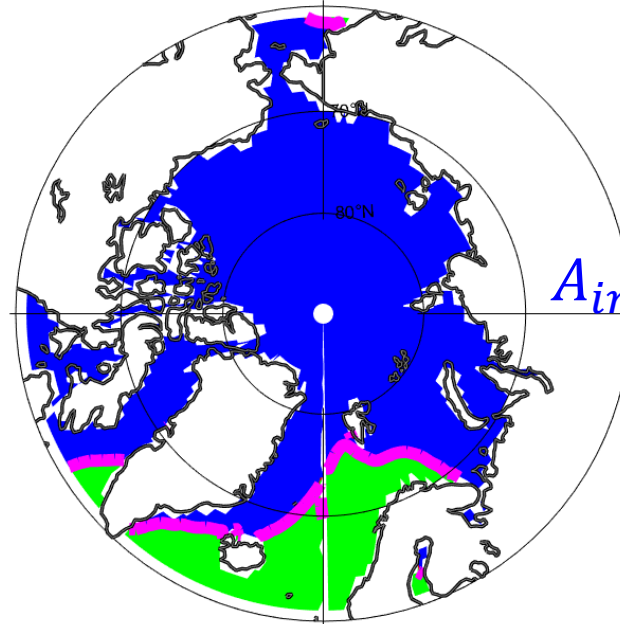


Breaking down albedo: a new definition for ice albedo difference and sea ice concentration difference

$$\alpha = \alpha_{ir} A_{ir} + a_{or} (1 - A_{ir})$$

$$\alpha_{ir} = \alpha_{i_{ir}} c_{ir} + \alpha_{o_{ir}} (1 - c_{ir})$$

ocean albedo is calculated by averaging the surface albedo where sea ice concentration is less than 15%



A_{ir} : Ice region

15% sea ice concentration line

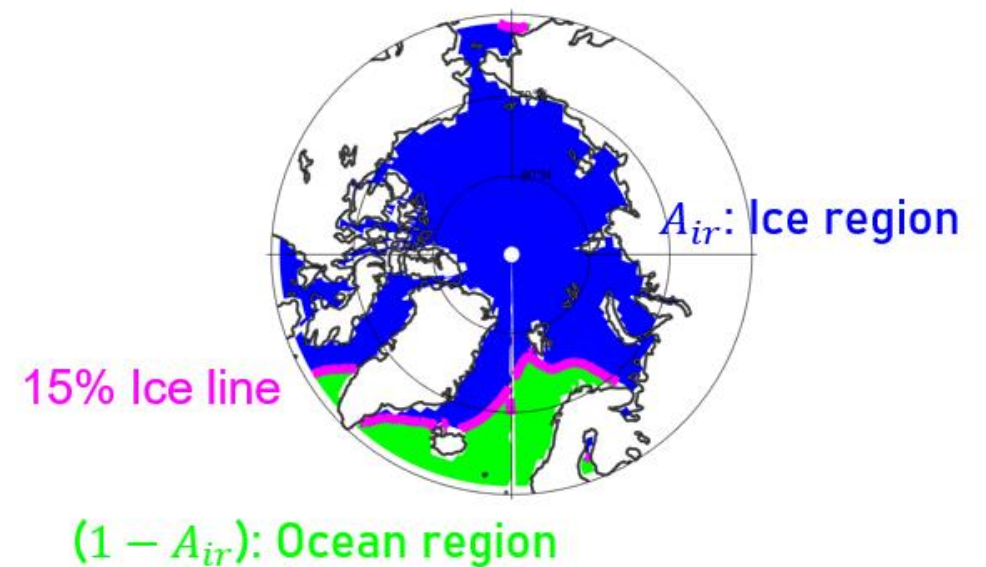
$(1 - A_{ir})$: Ocean region

Breaking down albedo: a new definition for ice albedo difference and sea ice concentration difference

$$\delta\alpha = \delta\alpha_{i\alpha} + \delta\alpha_c + \delta\alpha_{spv} + \delta\alpha_{IRA} + \delta\alpha_{o\alpha}$$

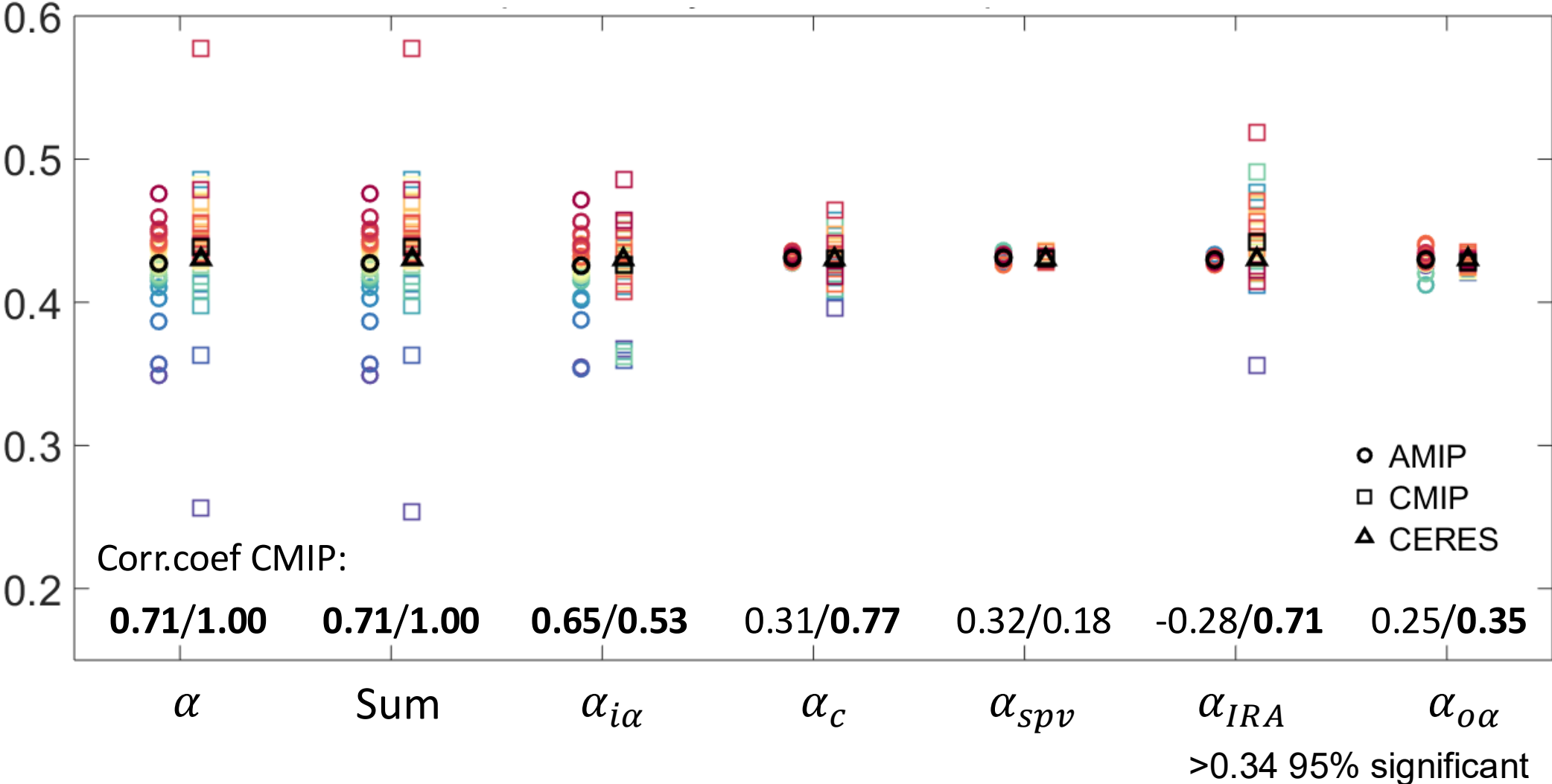
① ② ③ ④ ⑤

- ① Sea ice albedo in ice region
- ② Sea ice concentration in ice region
- ③ Albedo spatial variance term
- ④ Ice region term
- ⑤ Albedo in ocean region



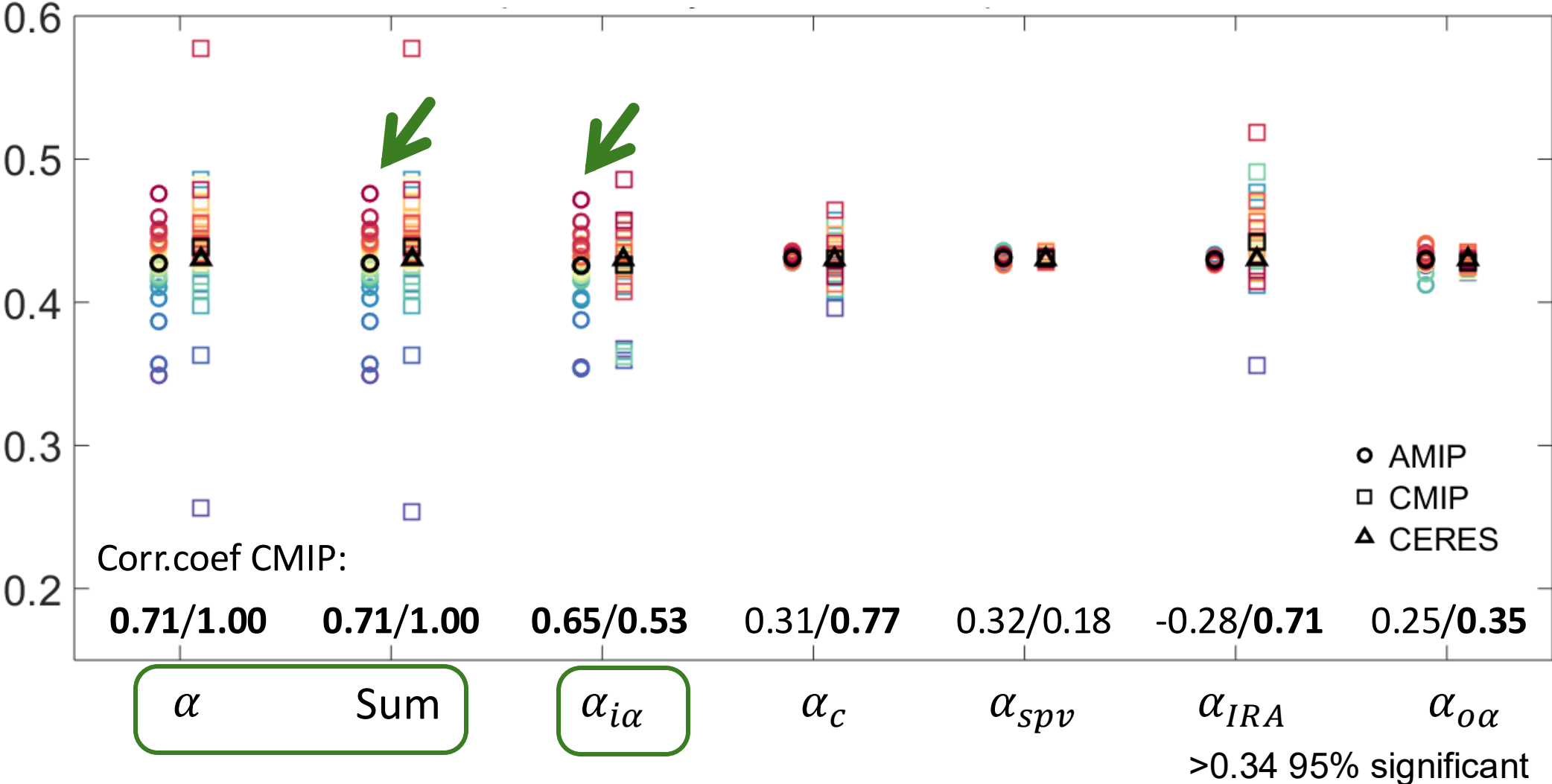
Consideration of surface **ice albedo** is a key component in modeling spread of surface albedo

surface albedo (α)



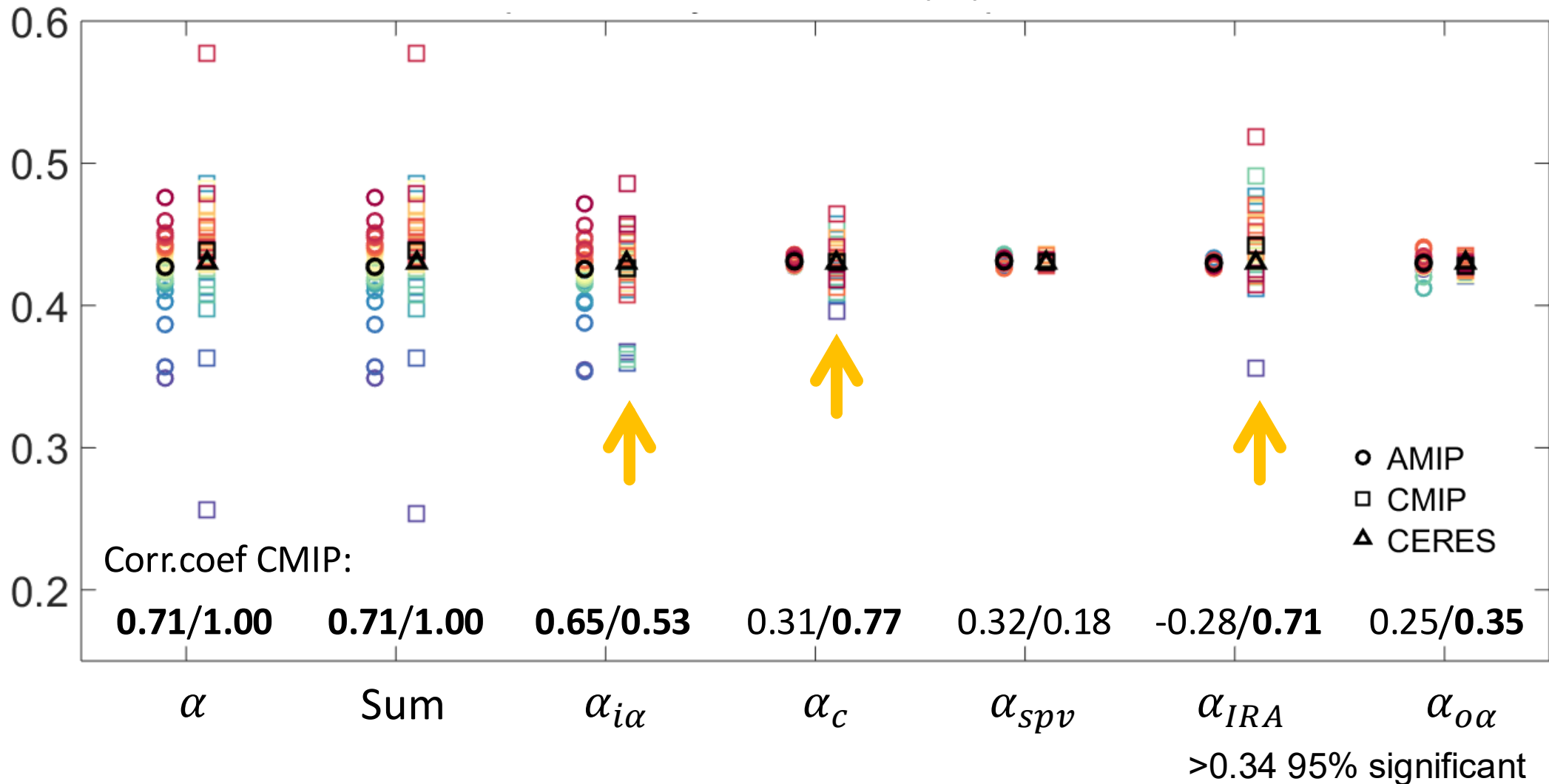
Consideration of surface **ice albedo** is a key component in modeling spread of surface albedo

surface albedo (α)

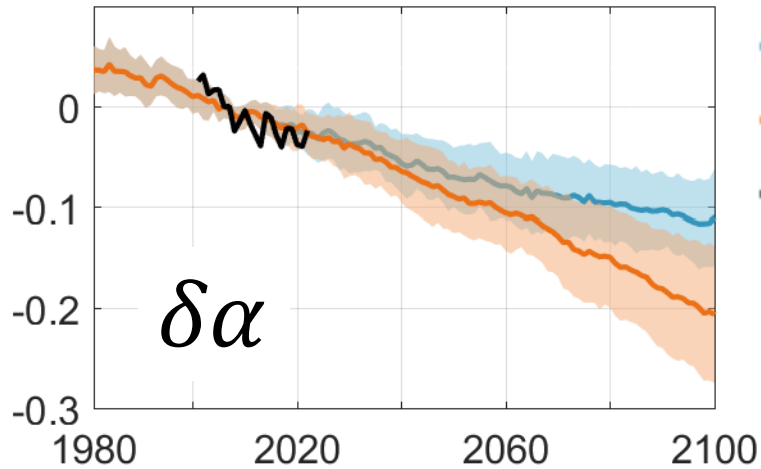


Consideration of surface **ice albedo** is a key component in modeling spread of surface albedo

surface albedo (α)

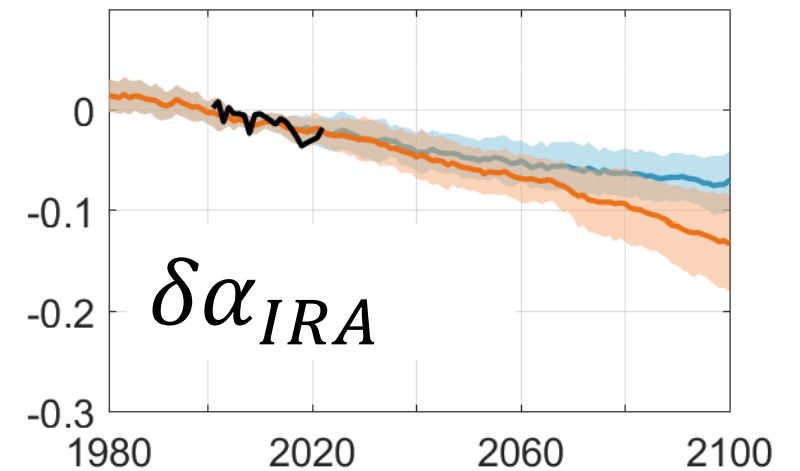
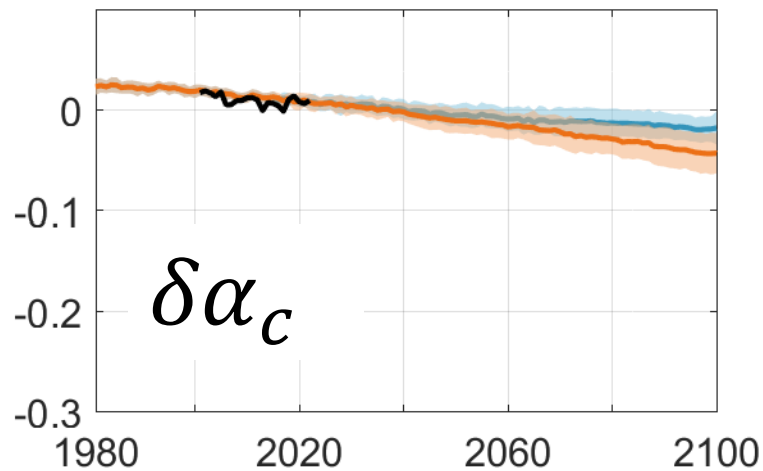
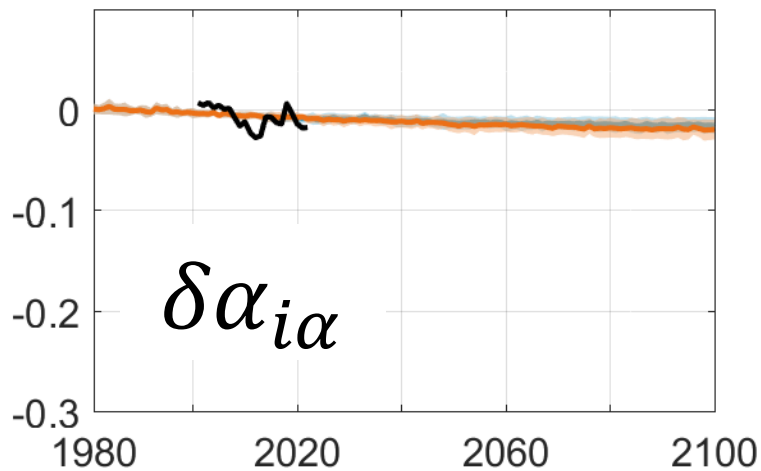


The temporal evolution of surface albedo changes closely follows the ice region term

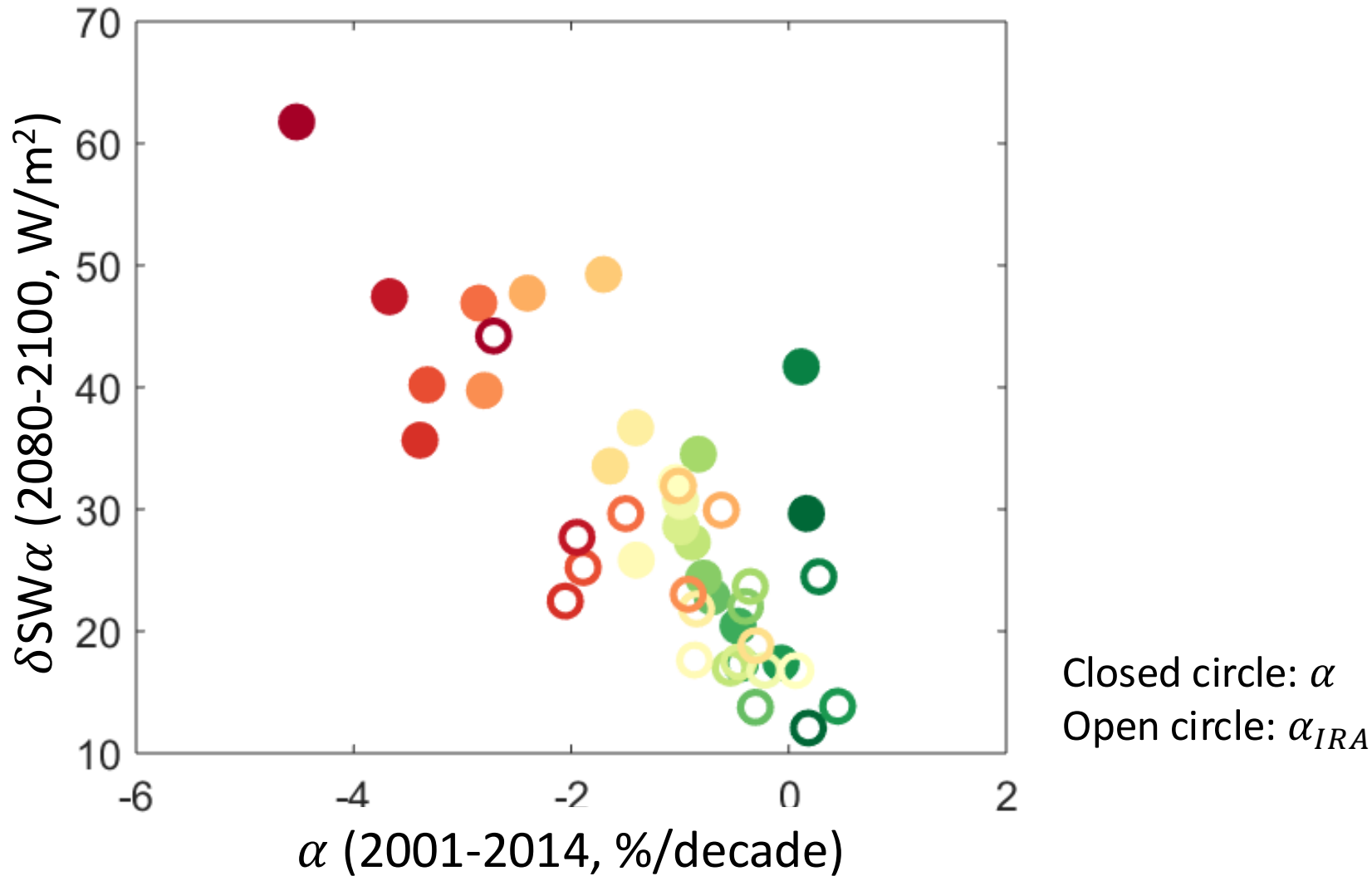


— SSP245
— SSP585
— CERES

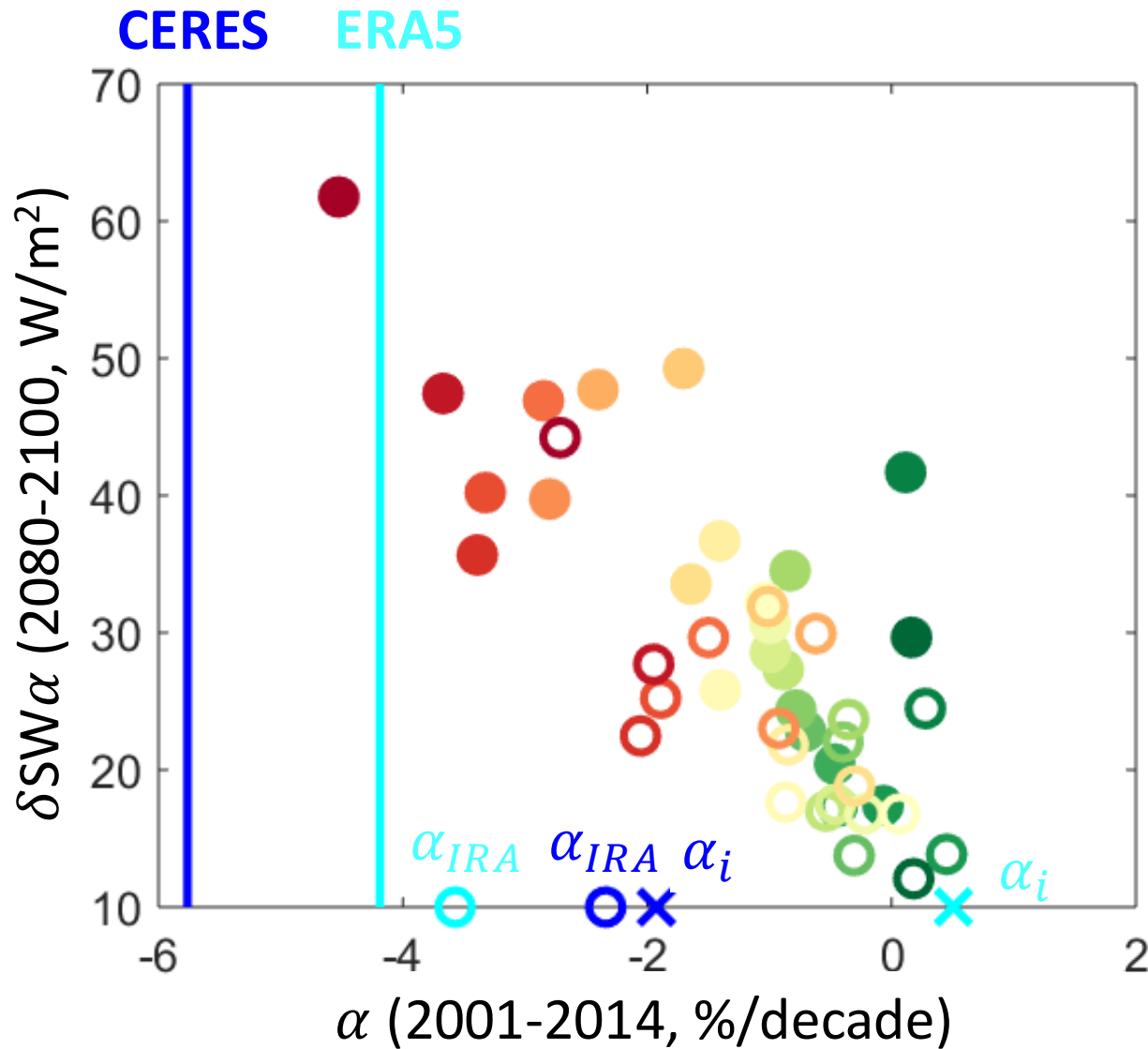
- CERES shows a sharp decline in trend until around 2010, with significant fluctuations affected by the sea ice albedo term
- Minimal variability of the sea ice albedo term in models compared to the considerable interannual variability and significant fluctuations in CERES



Greater declines in albedo in CMIP models in the present day indicate more future SW changes due to albedo

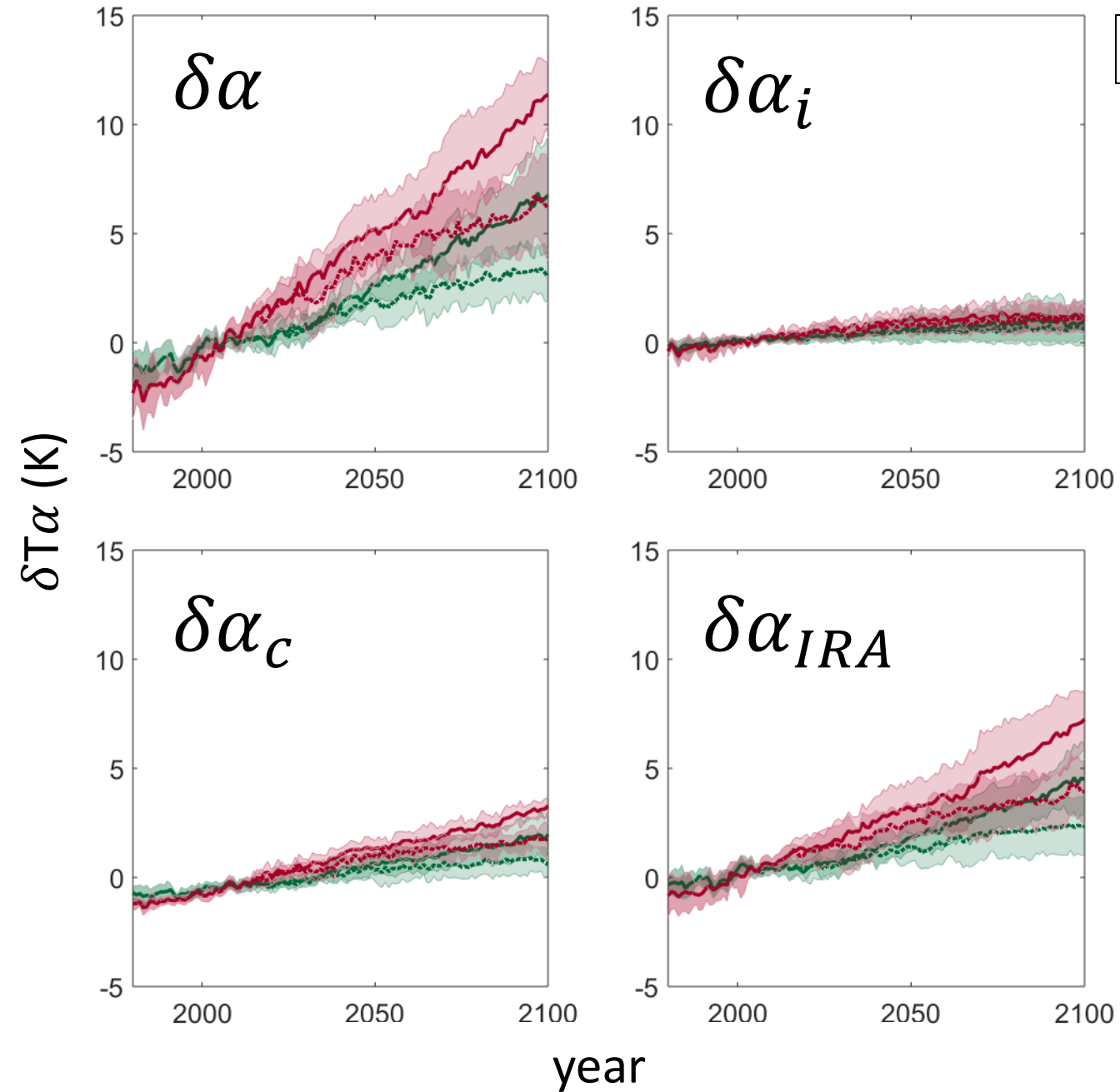


Greater declines in albedo in CMIP models in the present day indicate more future SW changes due to albedo



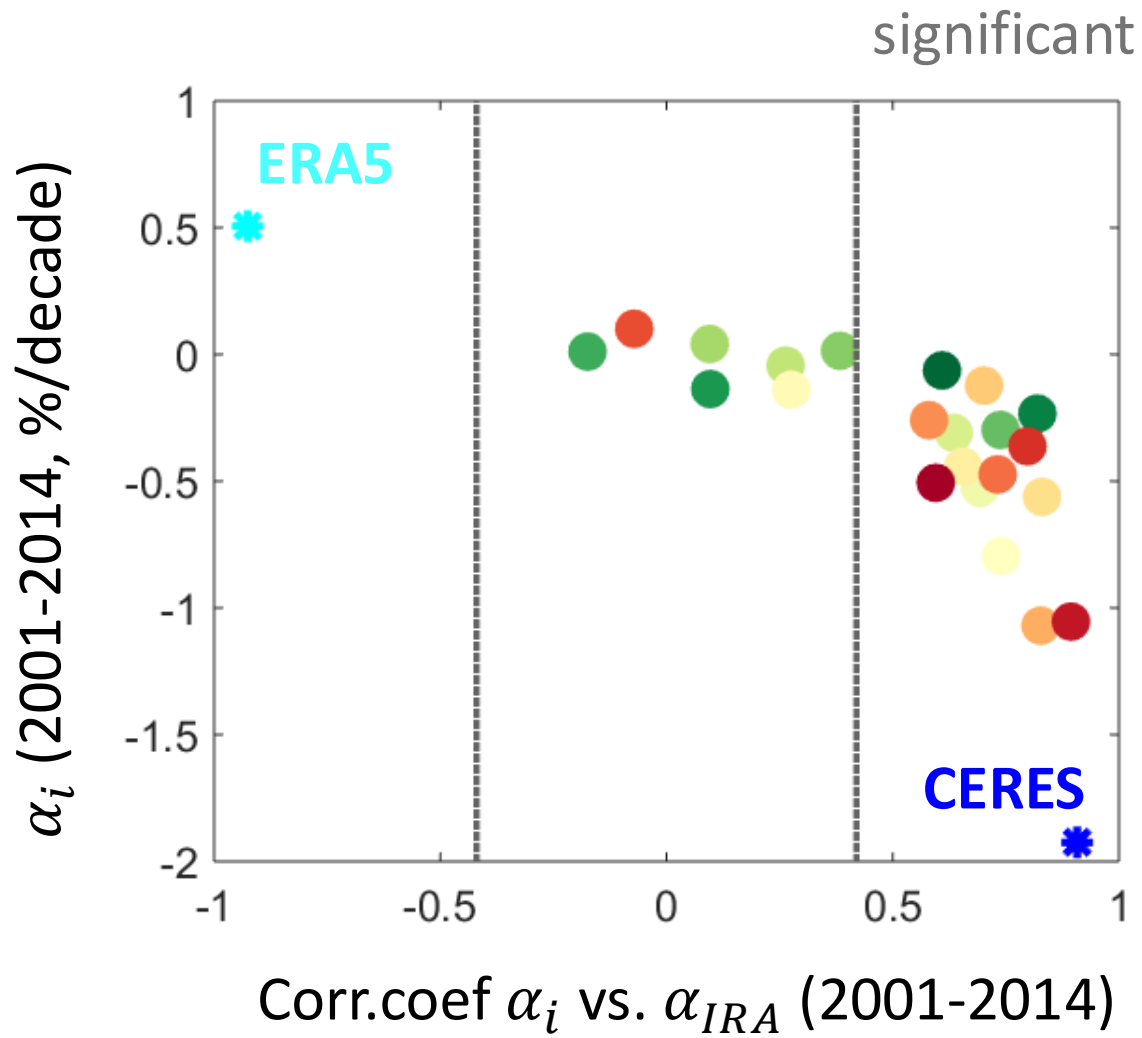
- Present-day declines in models are smaller compared to CERES and ERA5.
- In CERES, the decline in albedo is driven by both the ice region and ice albedo terms.
- However, ERA5 shows an opposite trend between the ice region and ice albedo terms.
- Hereafter, model n=22

Closed circle: α
Open circle: α_{IRA}



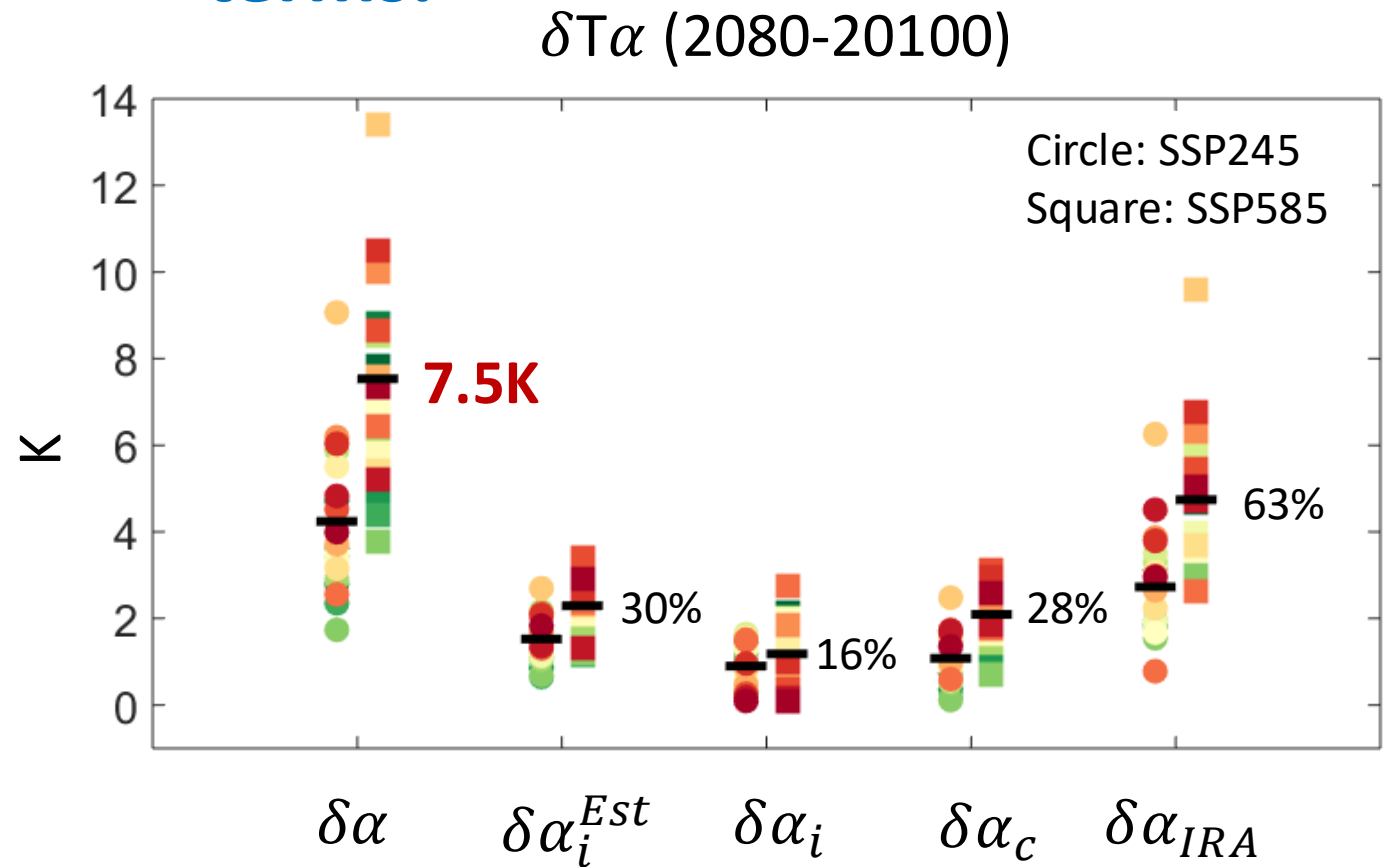
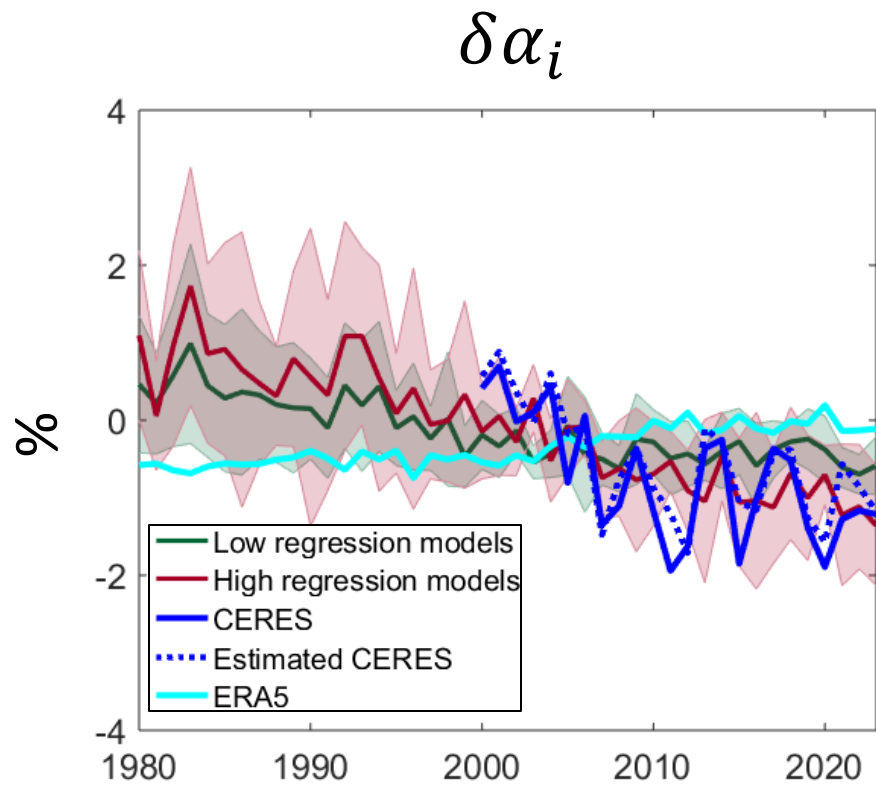
- The figure clearly shows that IRA is an important factor in the decline of albedo in the future.
- Models with greater declines in the present day tend to show larger declines in the future as well.

dash: SSP245
 solid: SSP585



- CERES shows high correlation between α_i and α_{IRA} .
- If there is a strong correlation between α_i and α_{IRA} , it indicates a more pronounced declining trend.
- The model shows a much lower declining trend compared to CERES.
- ERA5 exhibits the opposite behavior.
- A correlation coefficient above 0.42 is considered significant.

Higher Arctic warming compared to the multi-model mean can be expected due to the declining rate of the ice region term in comparison with CERES and the inaccuracies of the ice albedo terms.



Summary

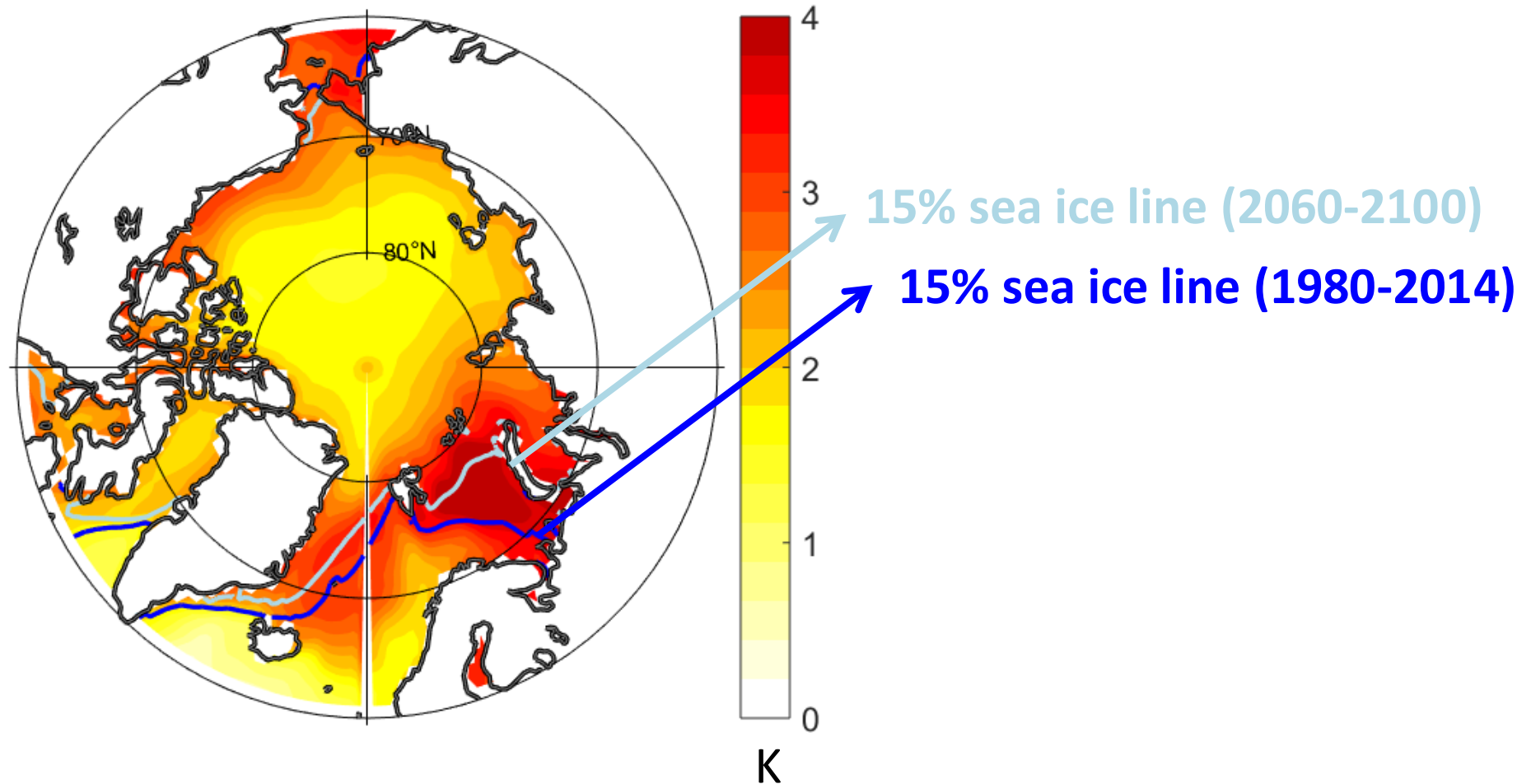
- **Despite the model mean of Arctic surface albedo agreeing with CERES**, the significant inter-model spread may be a primary factor contributing the variability observed in Arctic warming across different model simulations.
- The seasonal and regional analysis exposes differences in surface albedo between CERES and CMIP models
- **The Arctic albedo exhibits a significant inter-model spread**, even when sea ice is held constant in AMIP simulations
- Our analysis with a new albedo decomposition revealed that not only the ice fraction difference but **the variance in ice albedo** has a substantial effect on the model spread in albedo.
- Time series data from historical and SSP scenarios indicates that sea ice albedo and concentration remain relatively unchanged in response to global warming, **while the ice region term decreases significantly over time.**
- Between 2000-2021, **CERES data indicates larger variability in the ice albedo term compared to the models.** This suggest that CMIP models might not fully capture the variability in ice albedo, suggesting the potential for greater variability in the near future than current model projections.

Supplementary

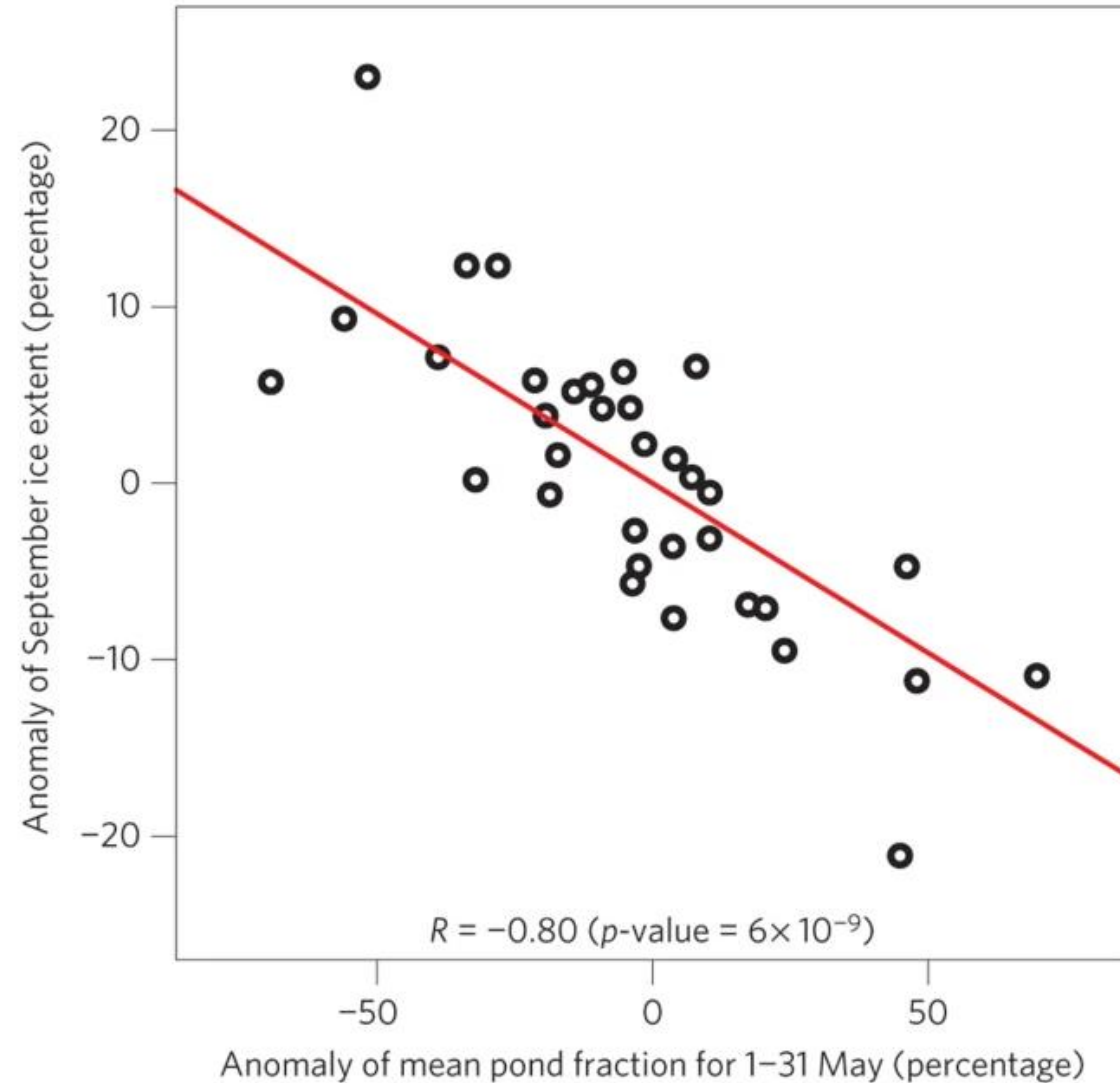
In the future, Ice region term will be important for explaining Arctic warming.

CMIP6 MMM Temperature response

$$(T_{2060-2100} - T_{1980-2014})$$



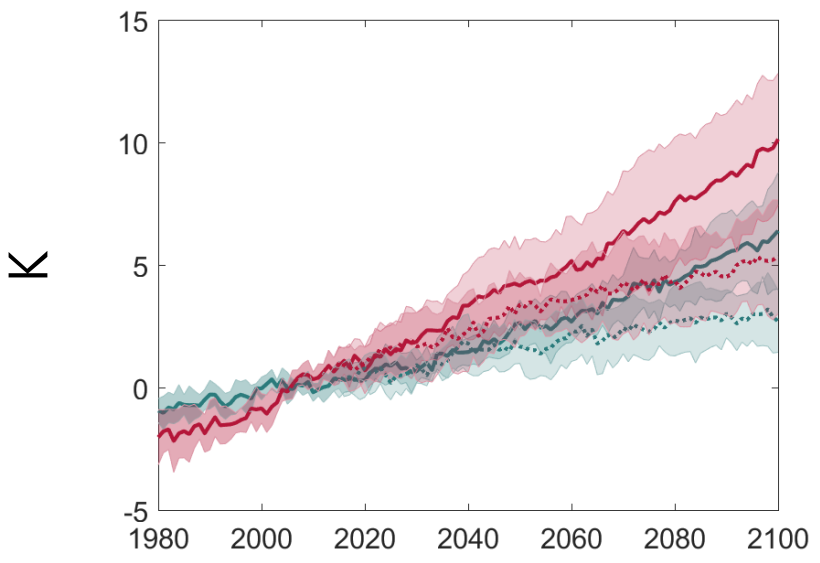
Variability in sea ice albedo has a substantial impact on the evolution of the Arctic climate system



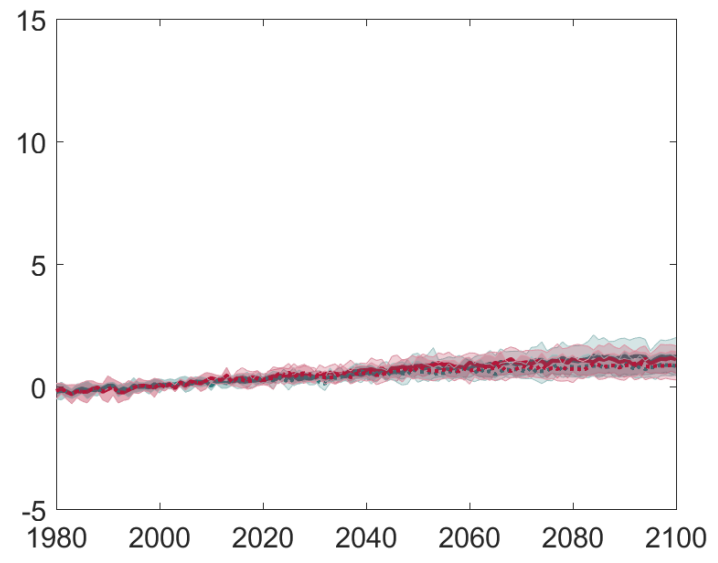
Schroder et al., 2014

Temperature response
from Kernel

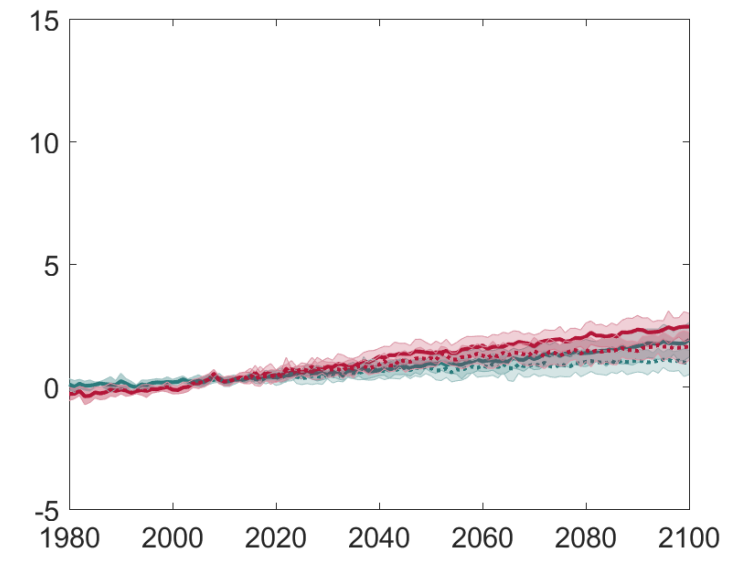
α



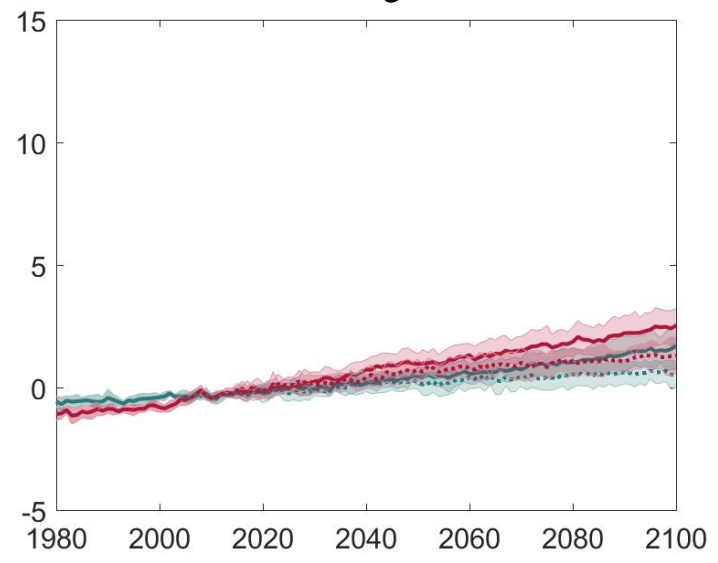
$\alpha_{i\alpha}$



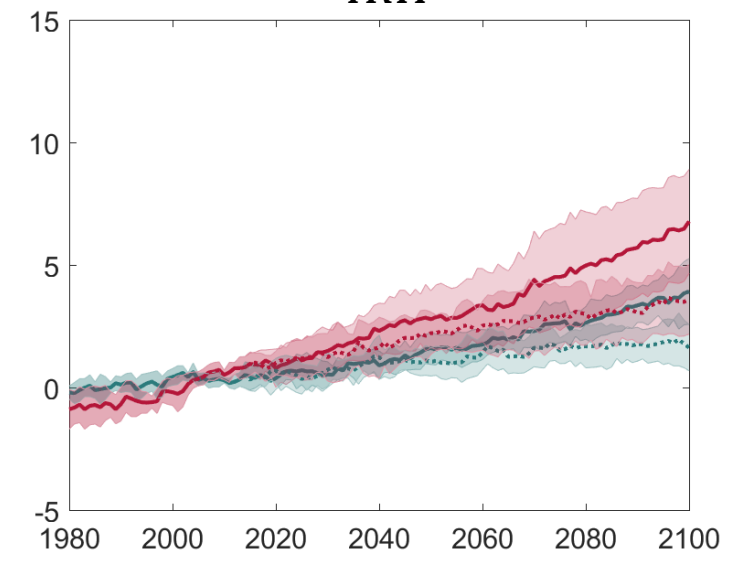
Estimated $\alpha_{i\alpha}$



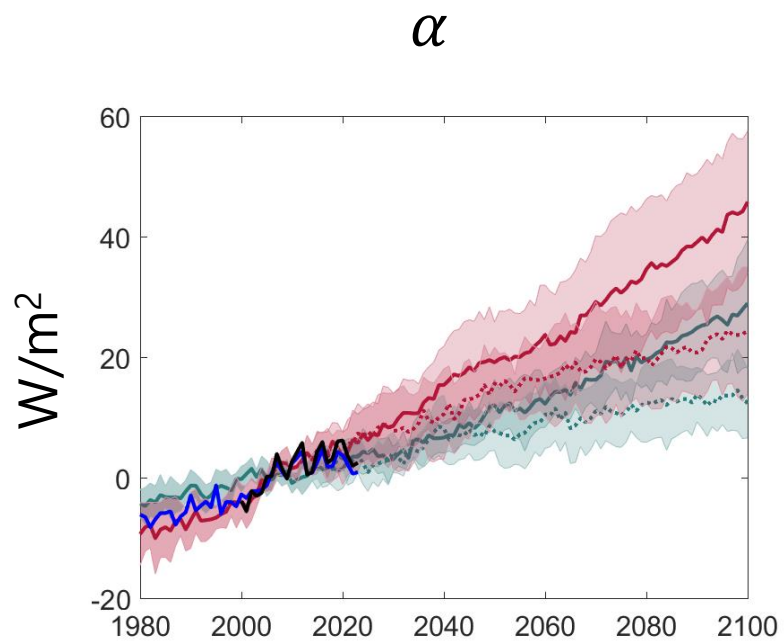
α_c



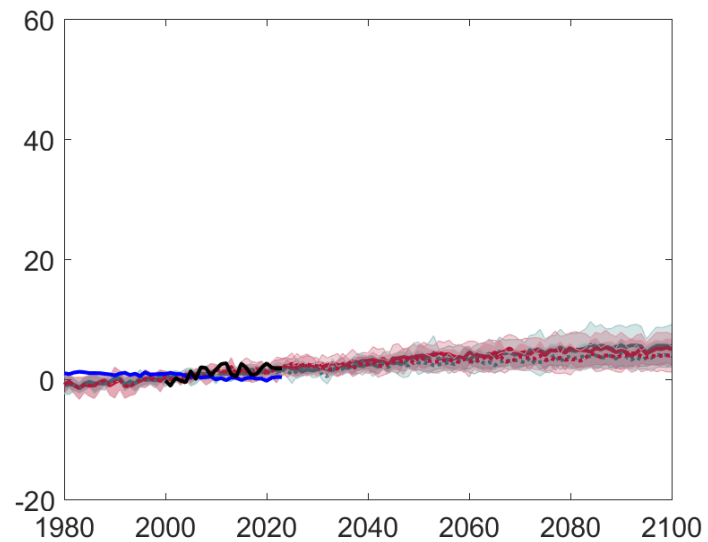
α_{IRA}



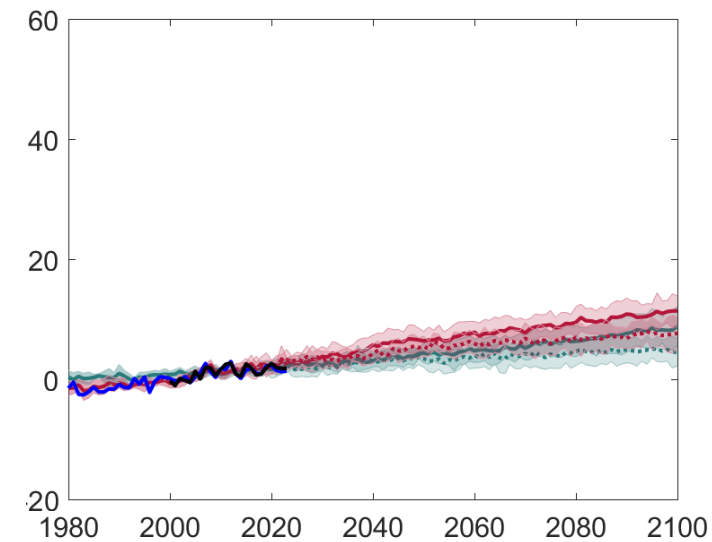
Albedo feedback



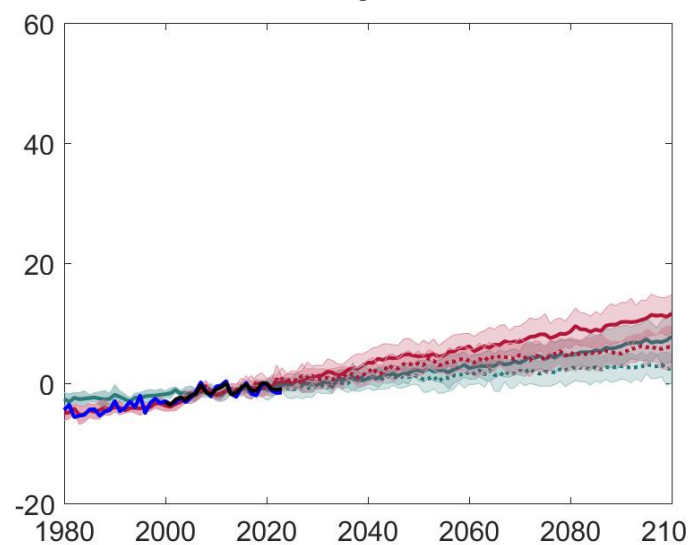
$\alpha_{i\alpha}$



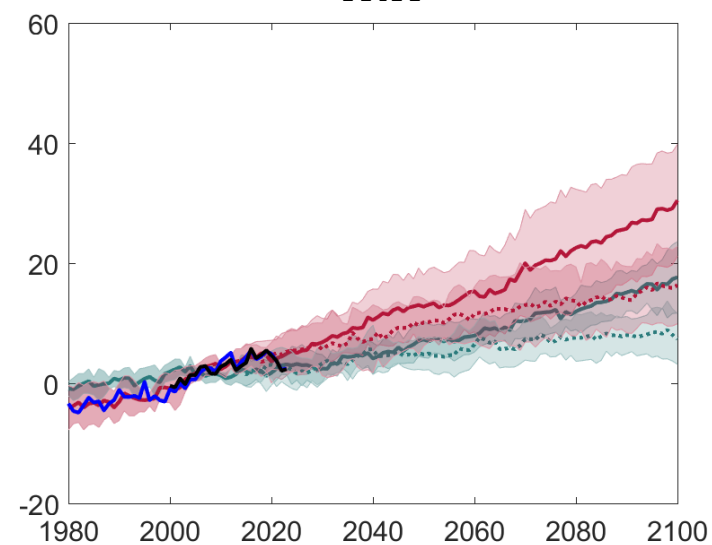
Estimated $\alpha_{i\alpha}$



α_c

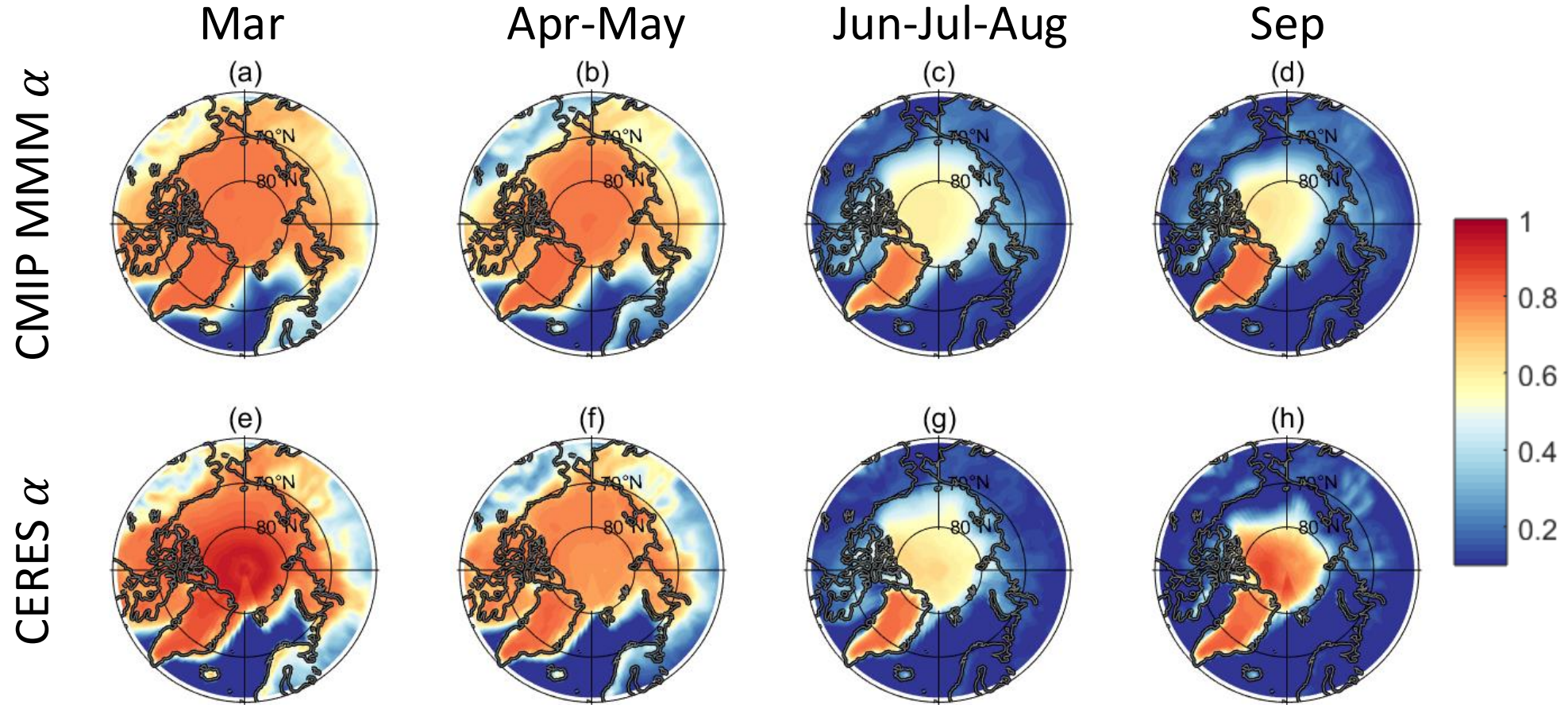


α_{IRA}

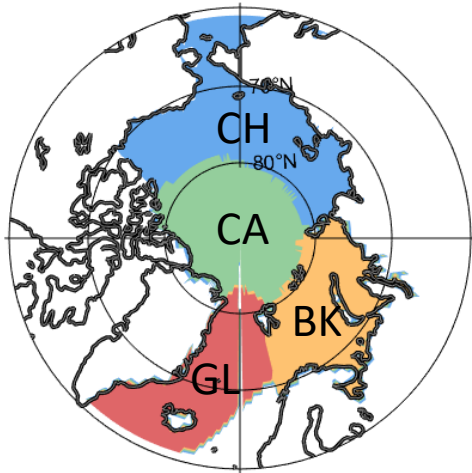


The seasonal and regional analysis exposes differences

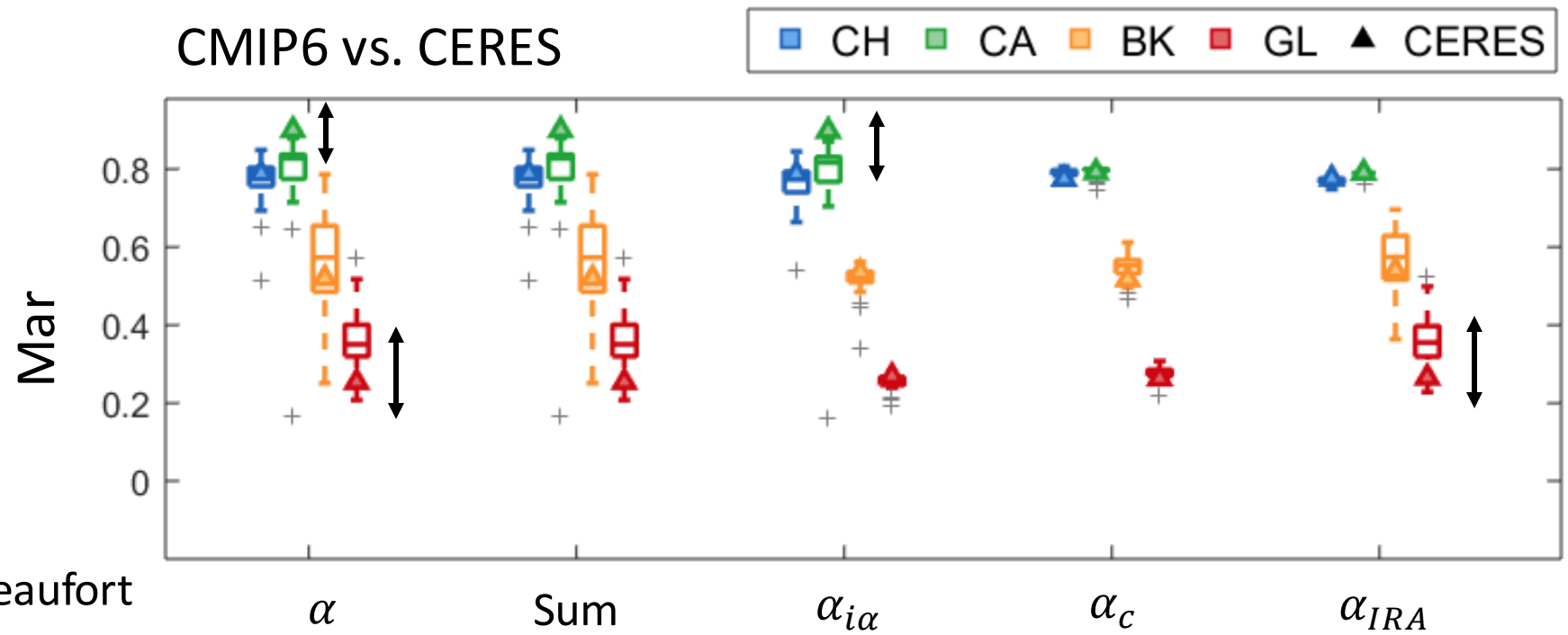
in surface albedo between CERES and CMIP models



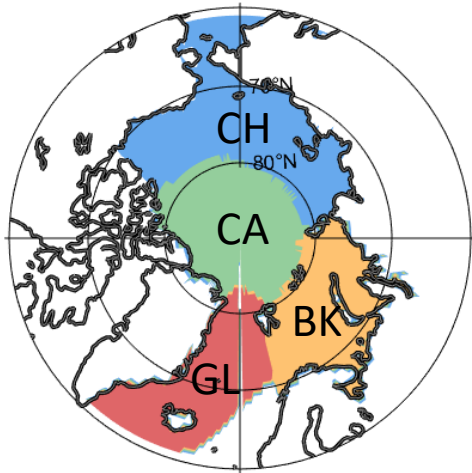
The seasonal and regional analysis exposes differences in surface albedo between CERES and CMIP models



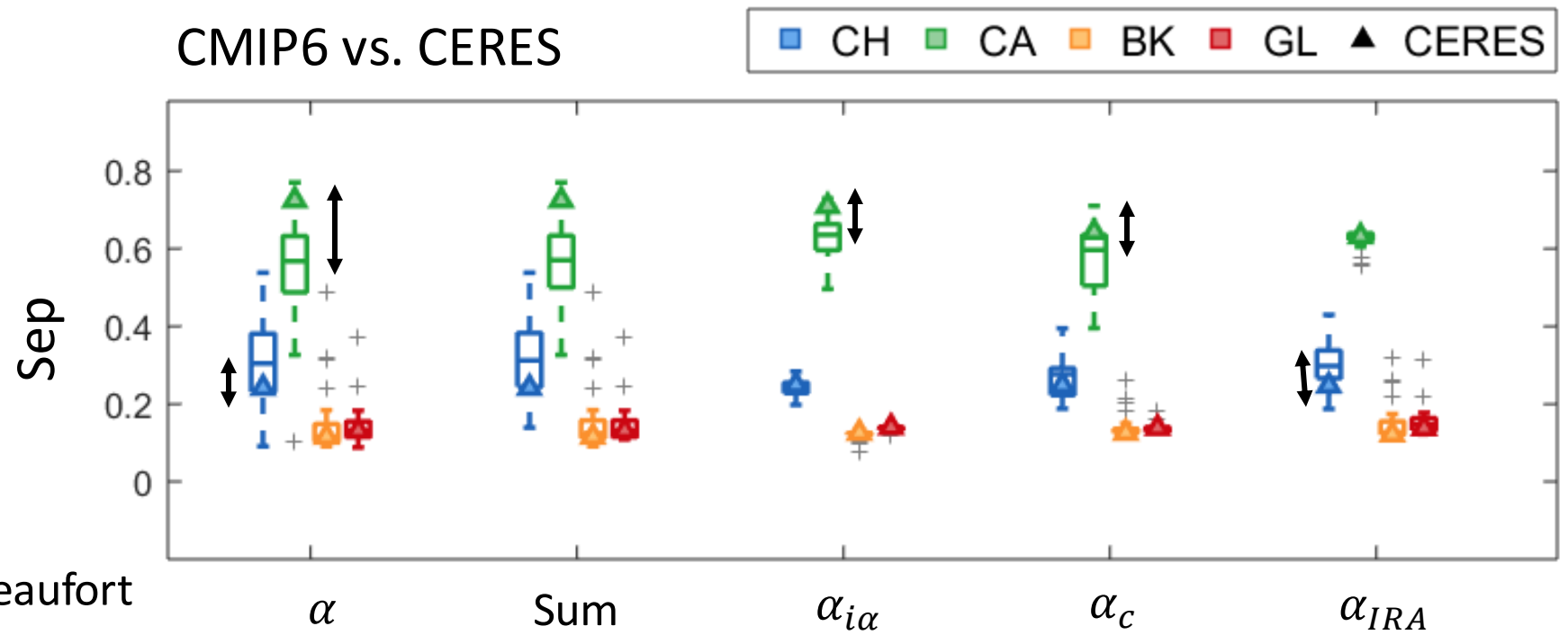
CH: East Siberian, Chukchi, & Beaufort
 CA: Central Arctic
 BK: Barents, Kara, & Laptev
 GL: Greenland sea



The seasonal and regional analysis exposes differences in surface albedo between CERES and CMIP models



CH: East Siberian, Chukchi, & Beaufort
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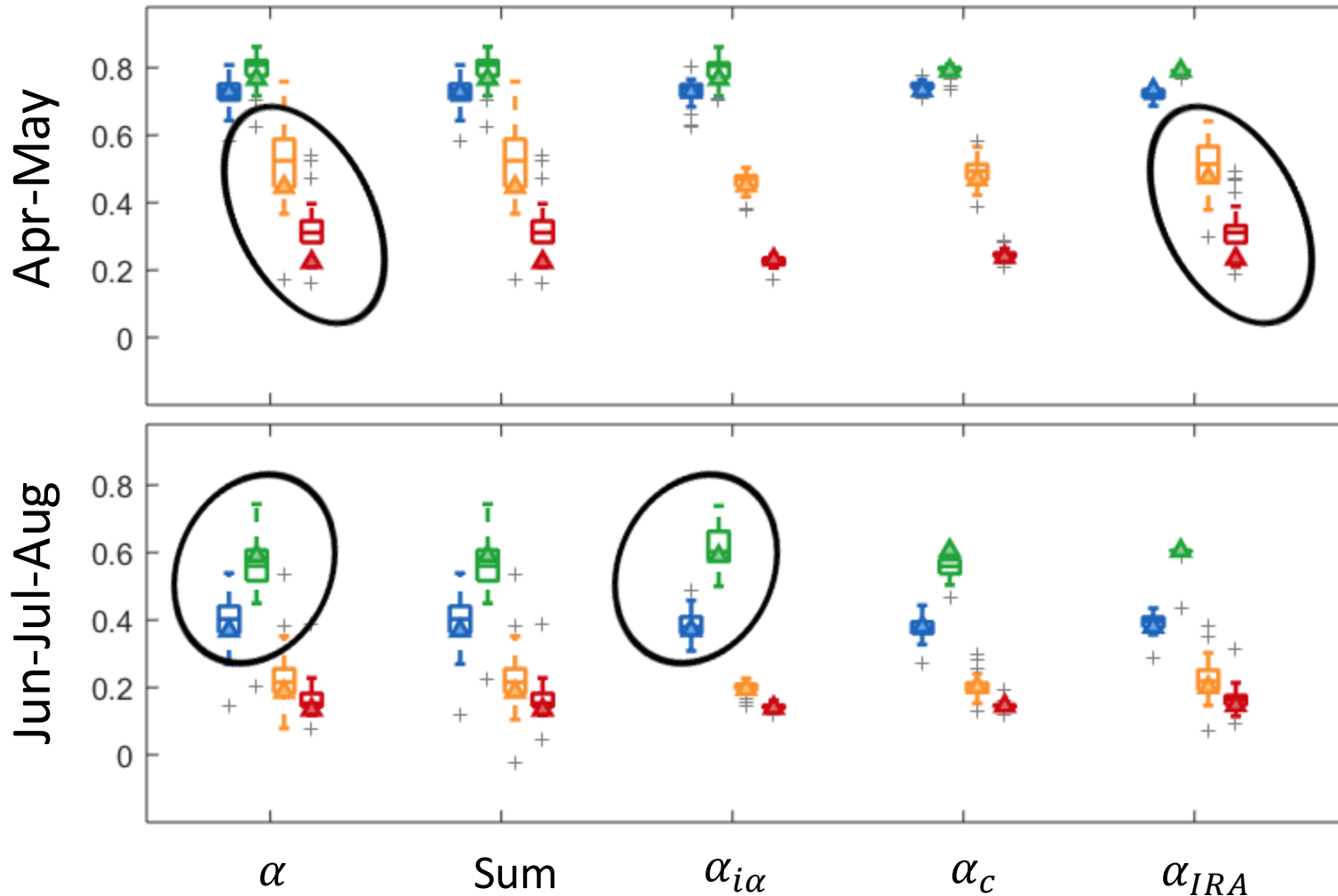


The large spread across CMIP models is significantly influenced

by α

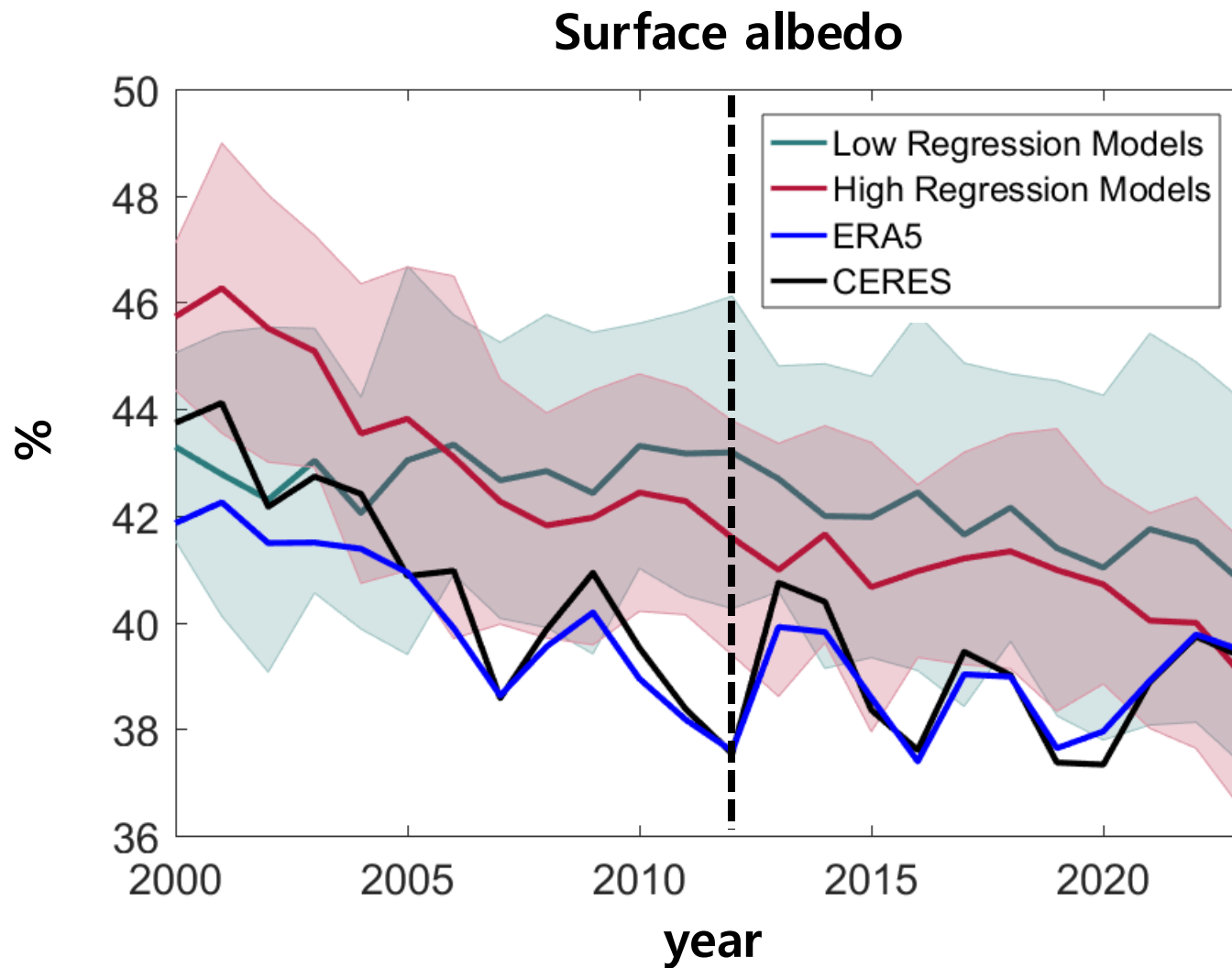
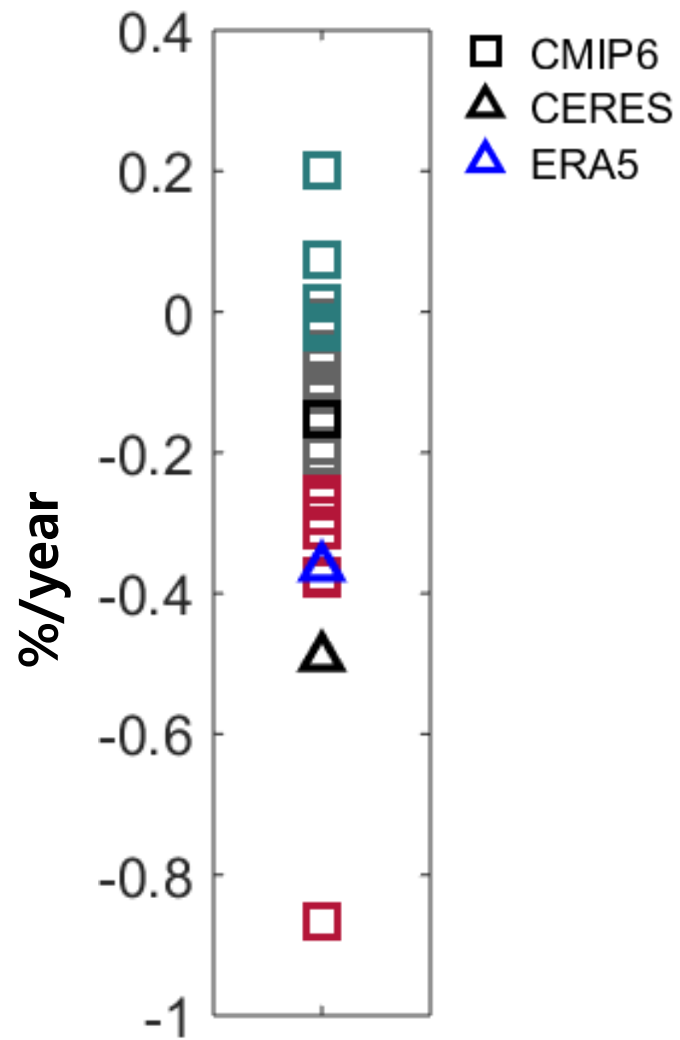


variations



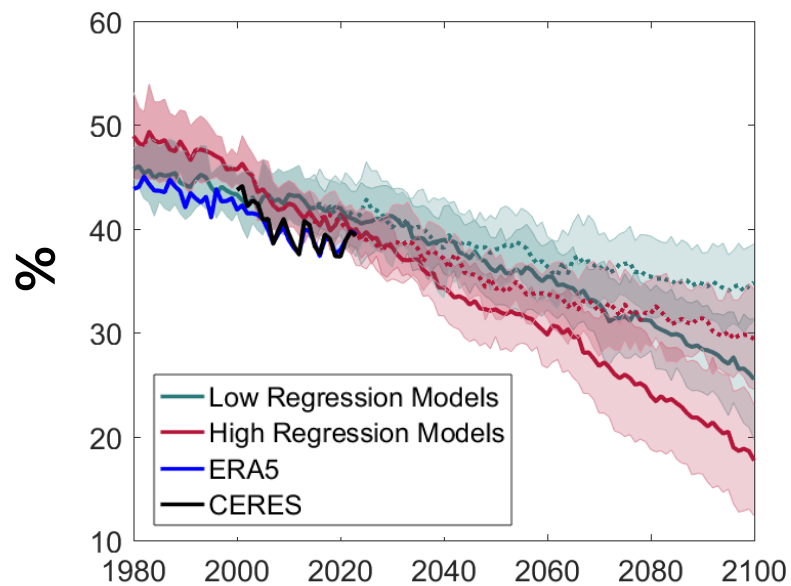
Early summer season:
Ice region term predominantly contributing to the albedo spread across the BK and GL

Late summer season:
Ice albedo term contributing to the albedo spread across the CH and CA



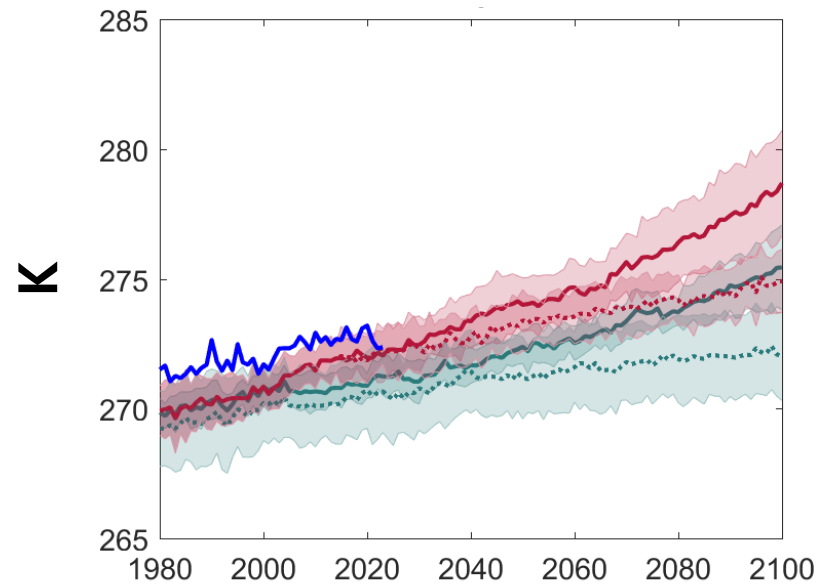
Arctic ocean (Apr-Aug)

Surface albedo

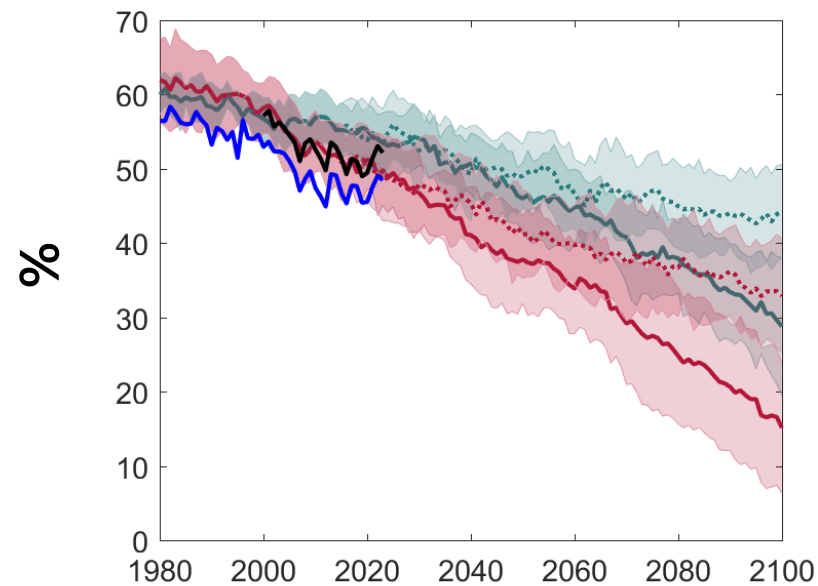


Solid: SSP585
Dotted: SSP245

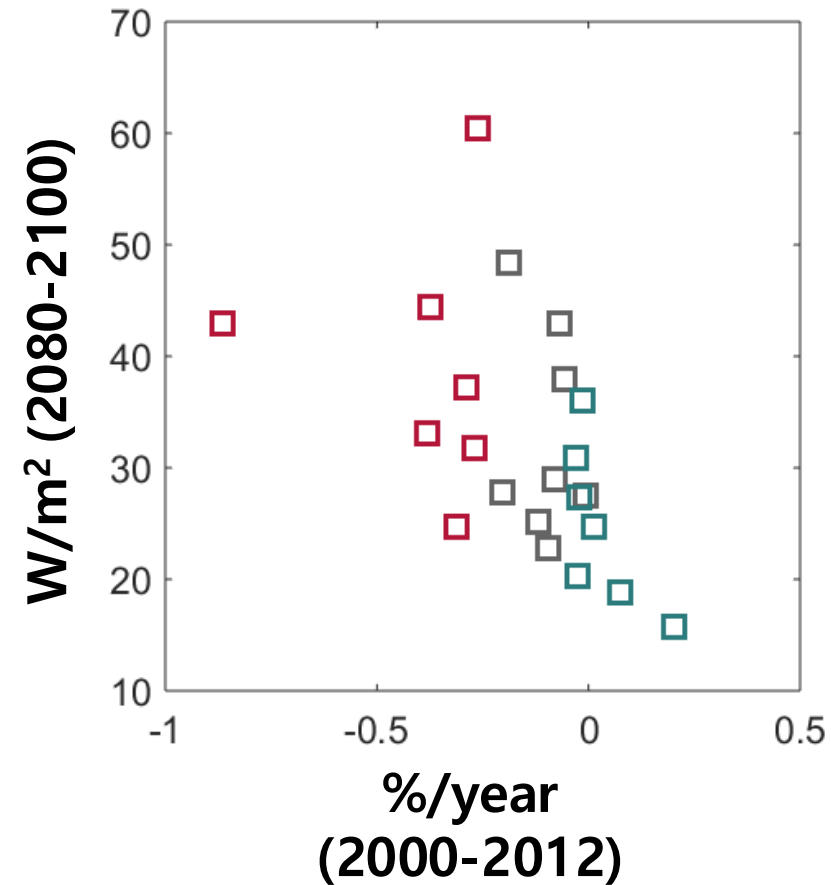
Surface temperature

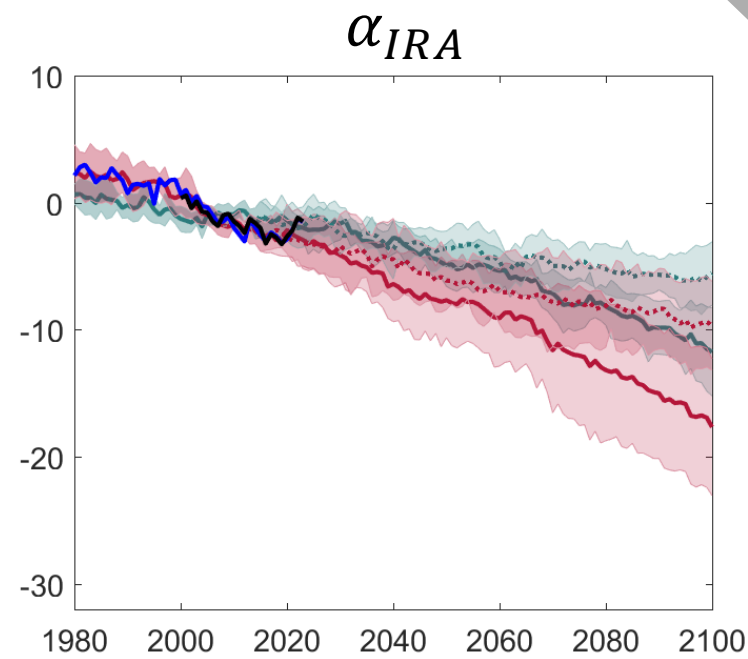
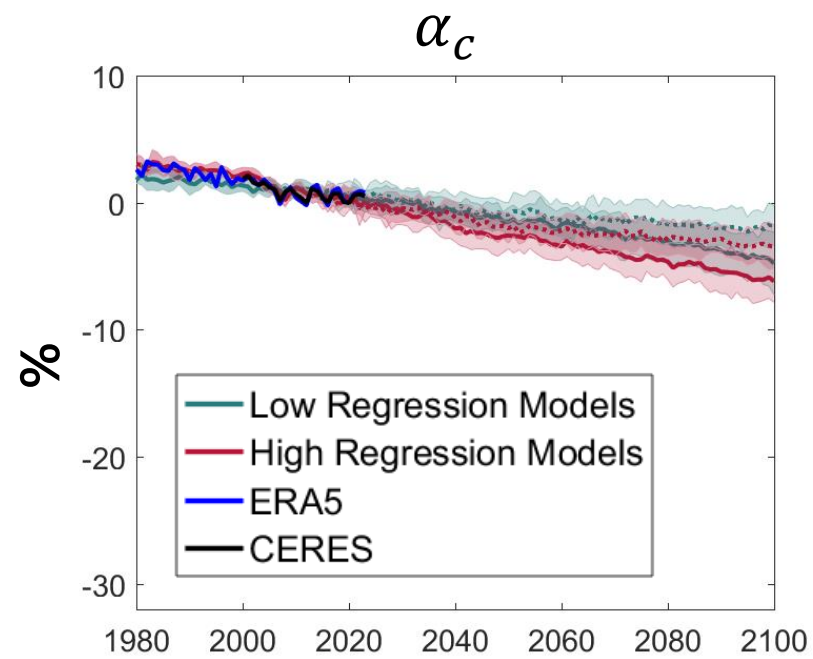
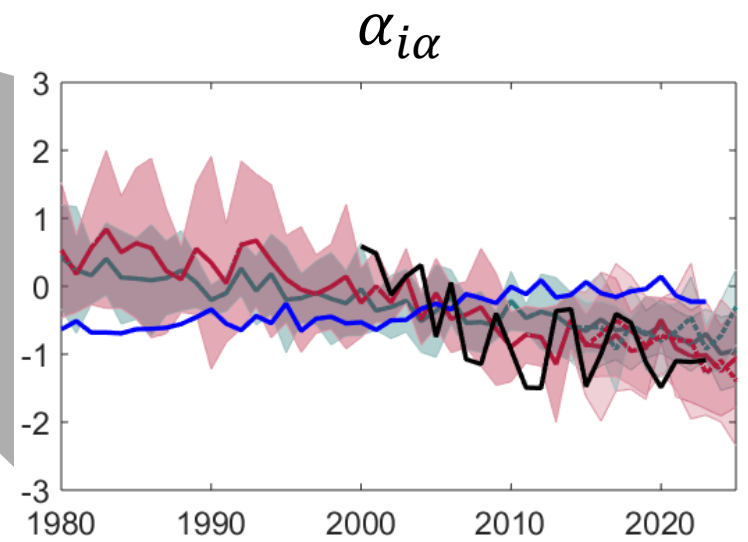
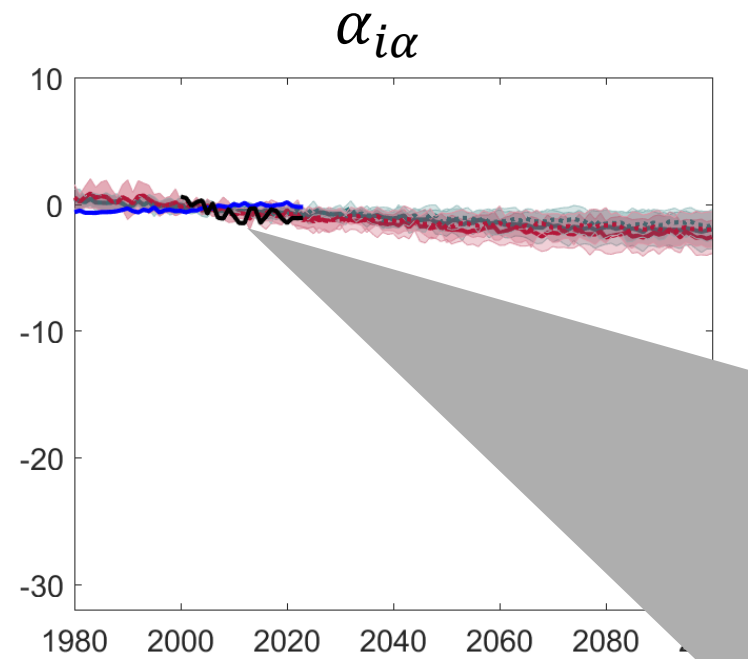
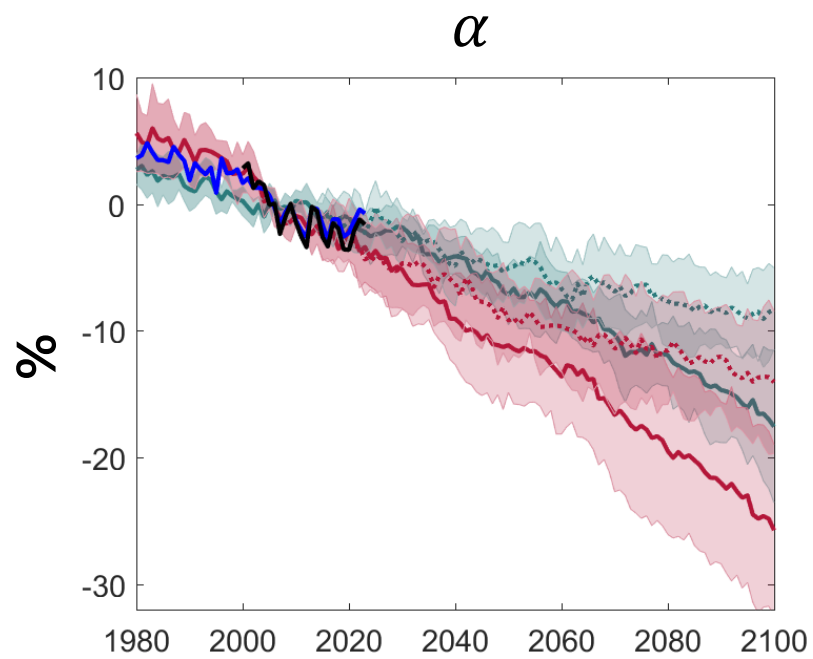


Sea ice concentration

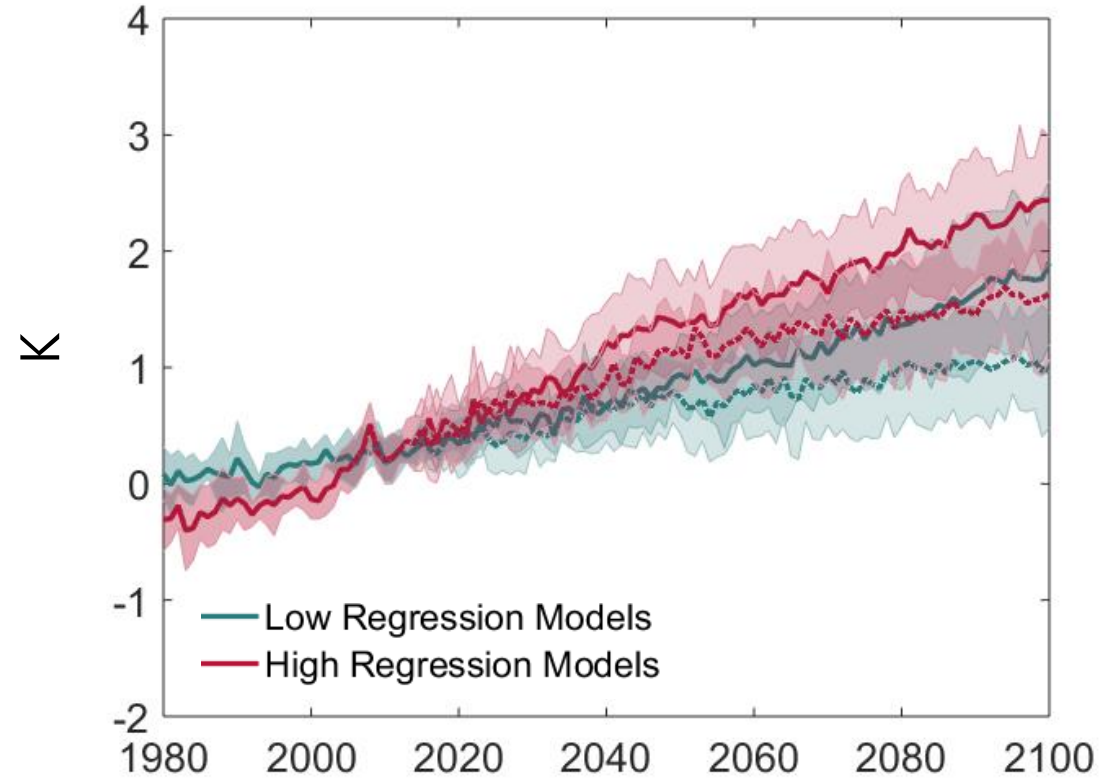


Regression vs. Albedo fbk

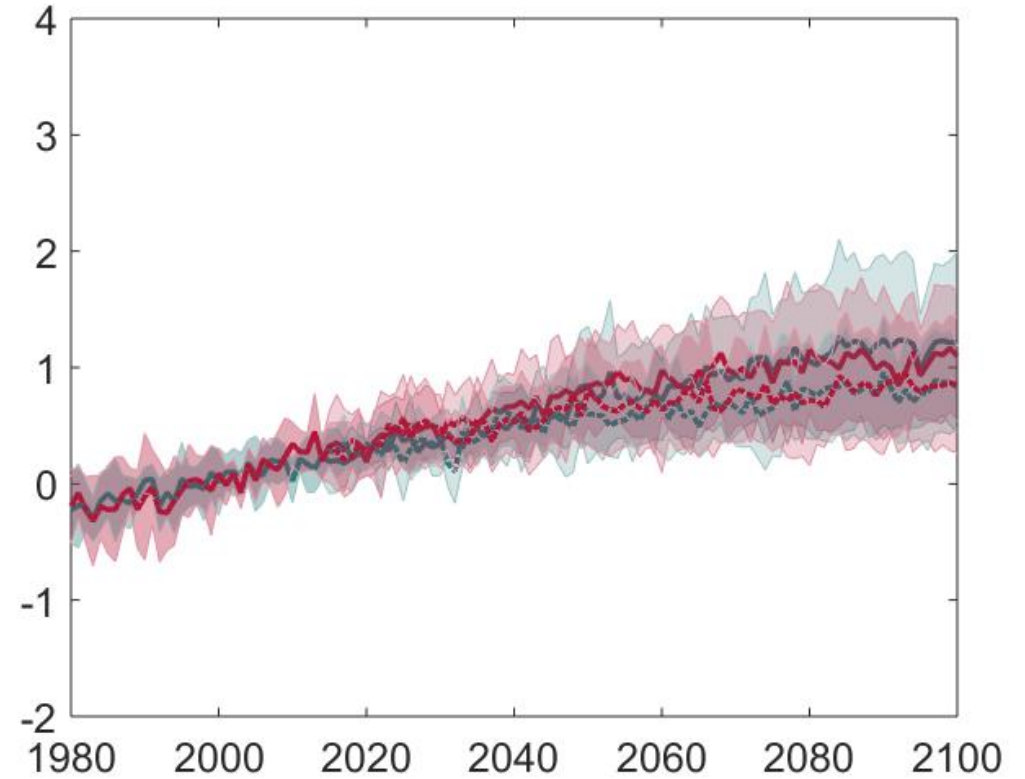




Temperature contribution from
Estimated α_{ia}

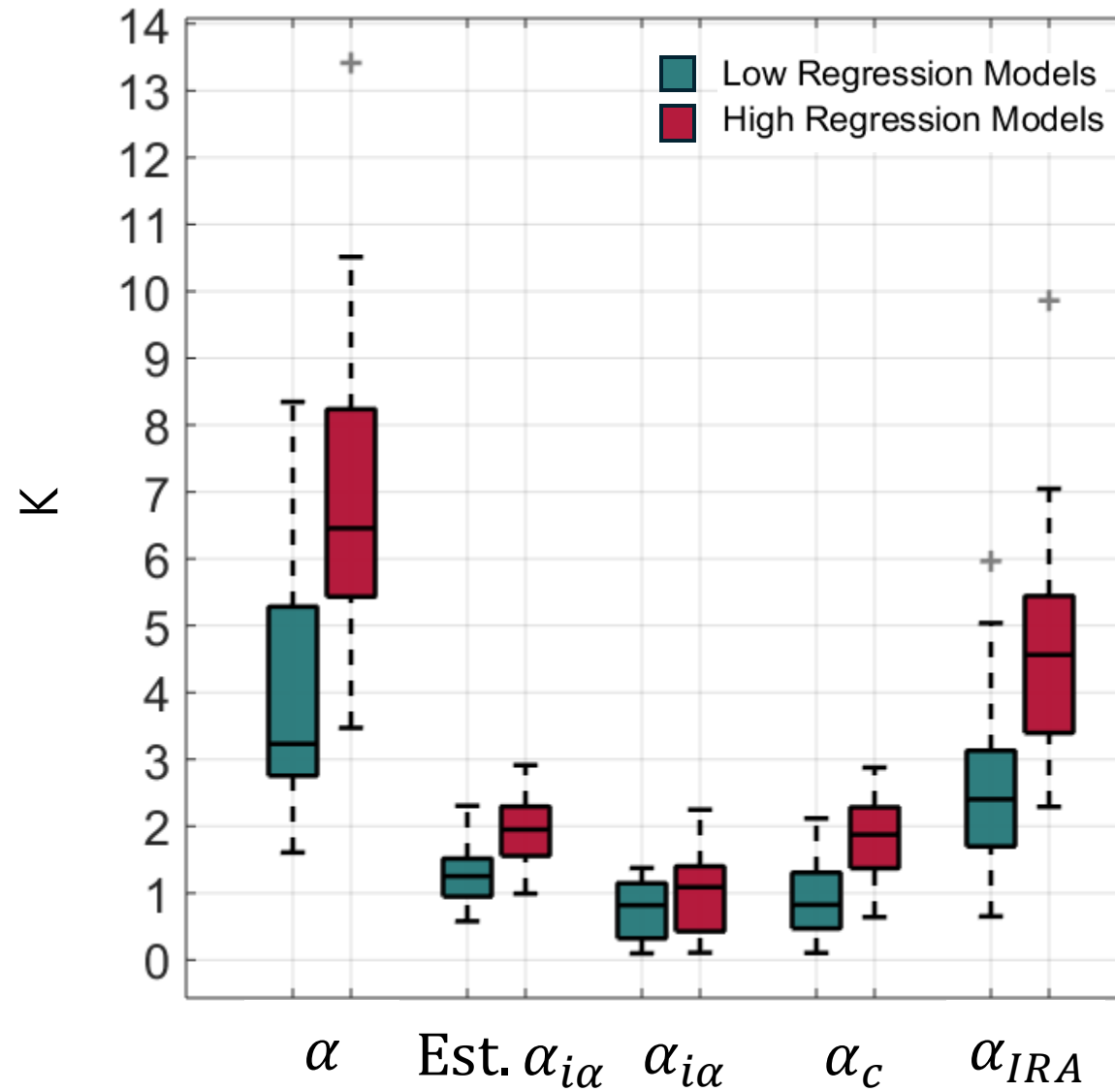


Temperature contribution from
 α_{ia}



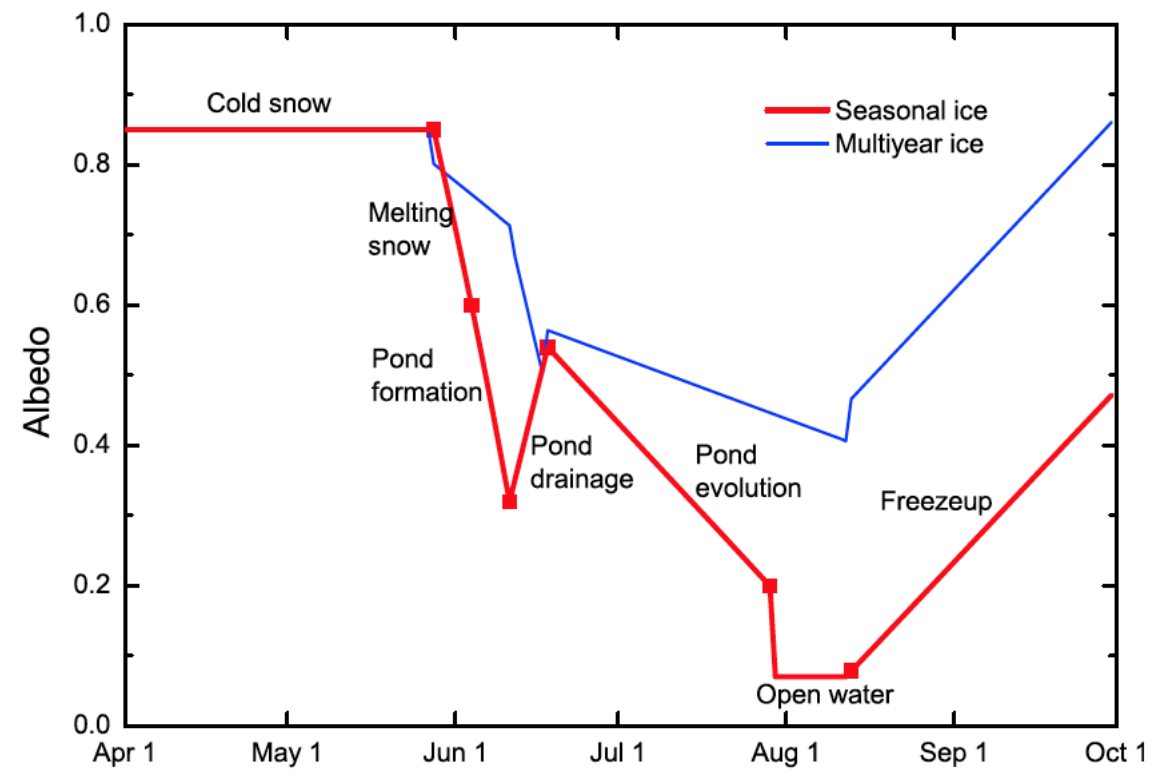
$$\text{Estimated } \alpha_{ia} = \beta_1 \alpha_c + \beta_2 \alpha_{IRA}$$

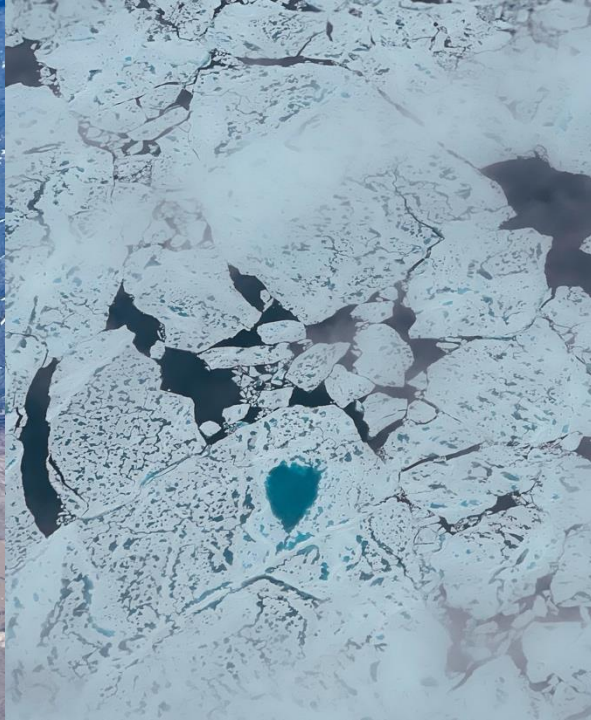
Temperature response (2080-2100)

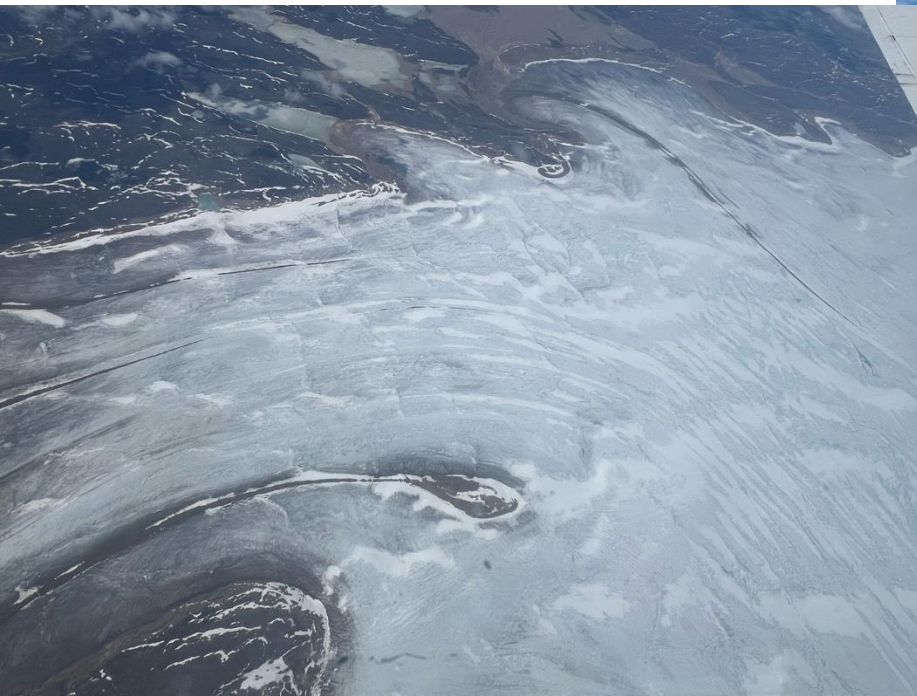
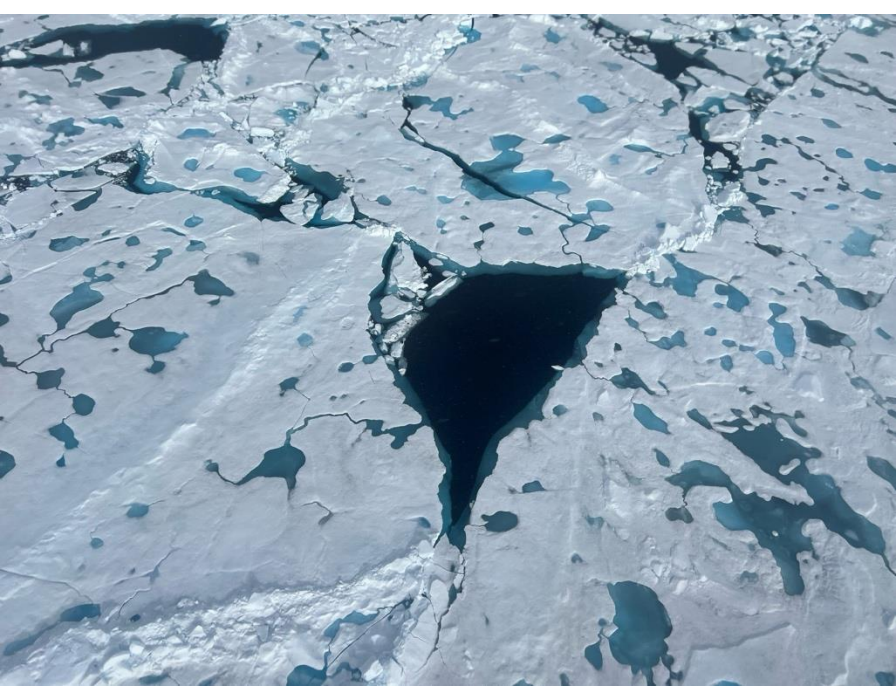




Variations in Arctic surface albedo







Many pictures of
Arctic surface albedo