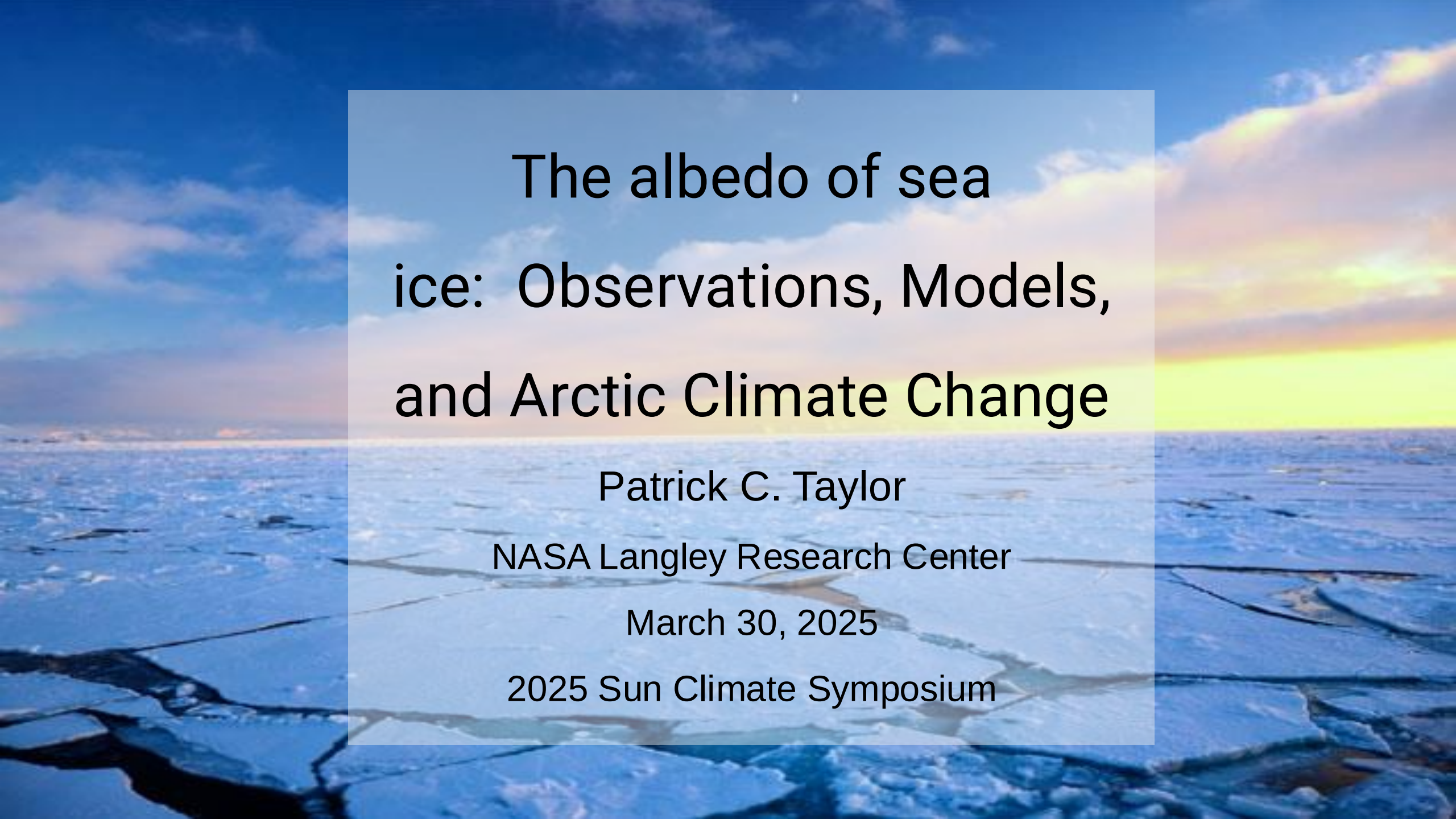


The albedo of sea ice: Observations, Models, and Arctic Climate Change

Patrick C. Taylor

NASA Langley Research Center

March 30, 2025

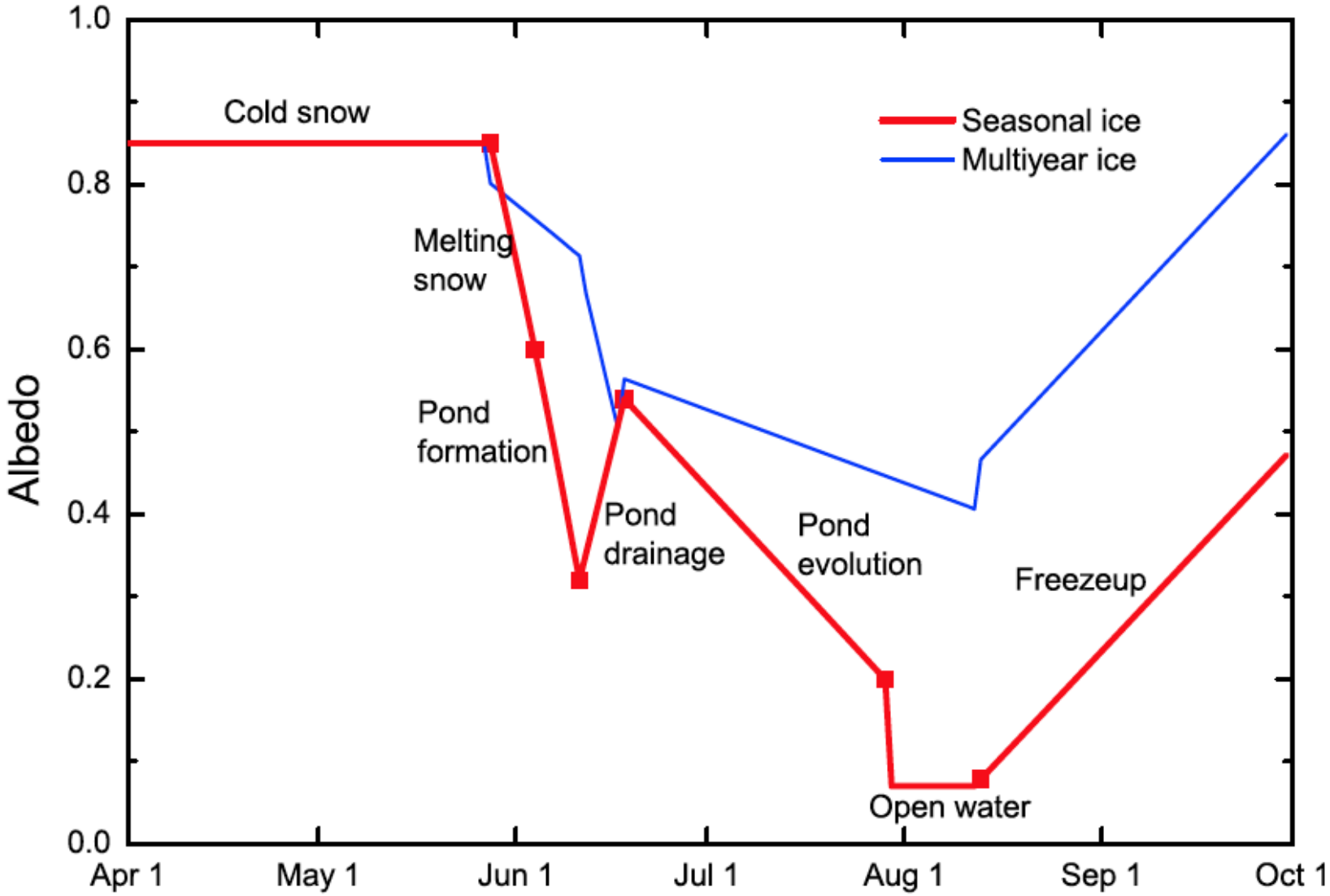
2025 Sun Climate Symposium

Key Takeaways:

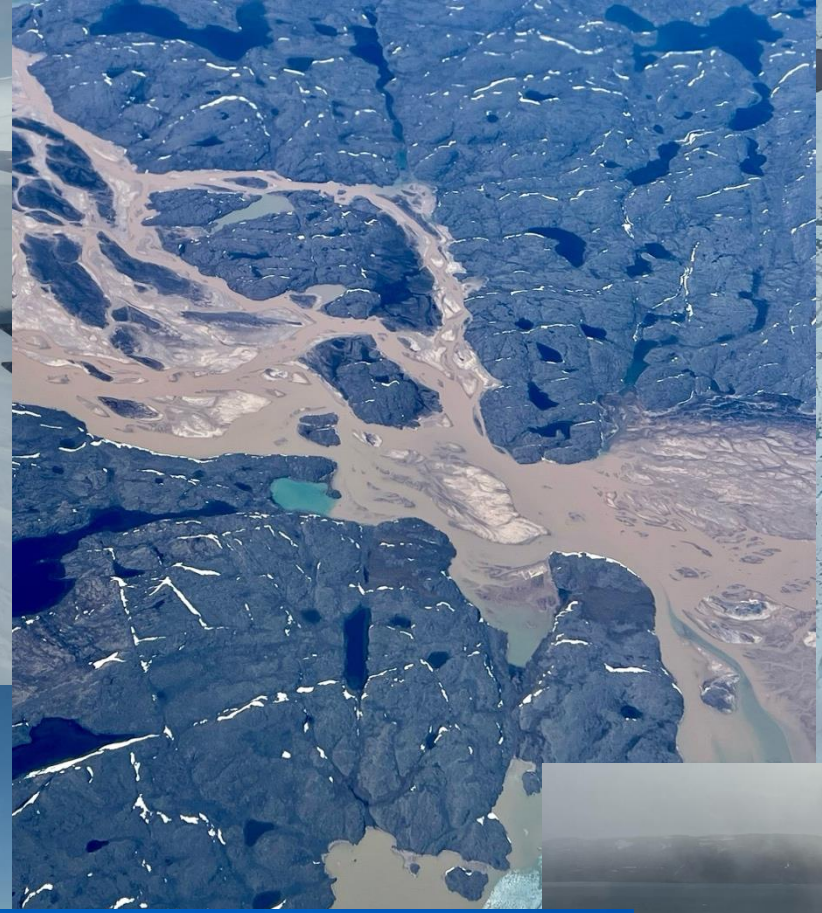
- **Arctic surface albedo remains a key source of uncertainty** in climate models for both present-day and projections of future change.
- **Projections of future Arctic warming are likely underestimated** based upon the current set of
- **Intera**
  subs
  missi
- We need an **focused, collective effort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

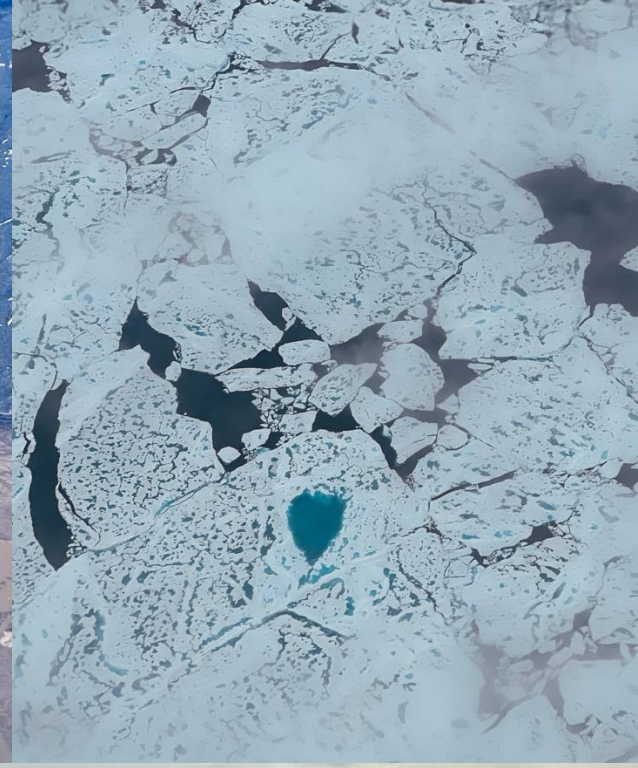
What is the seasonal variation in Arctic sea ice surface albedo?

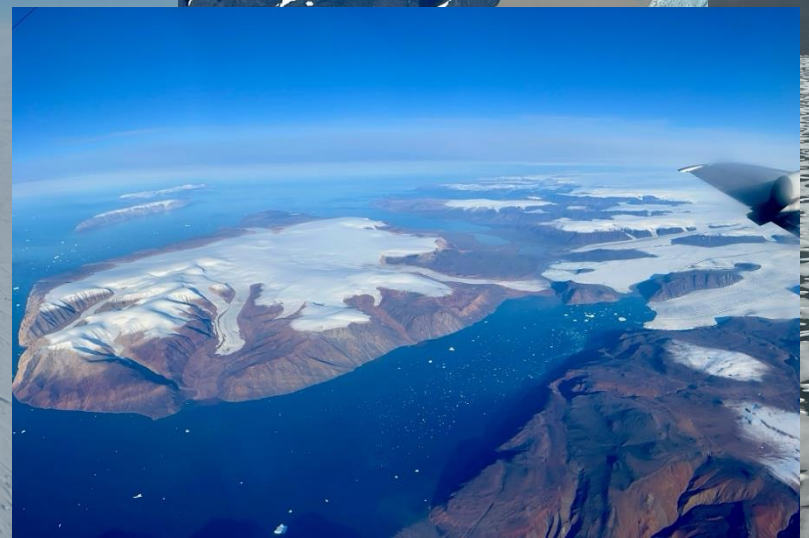
Variations in Arctic sea ice surface albedo



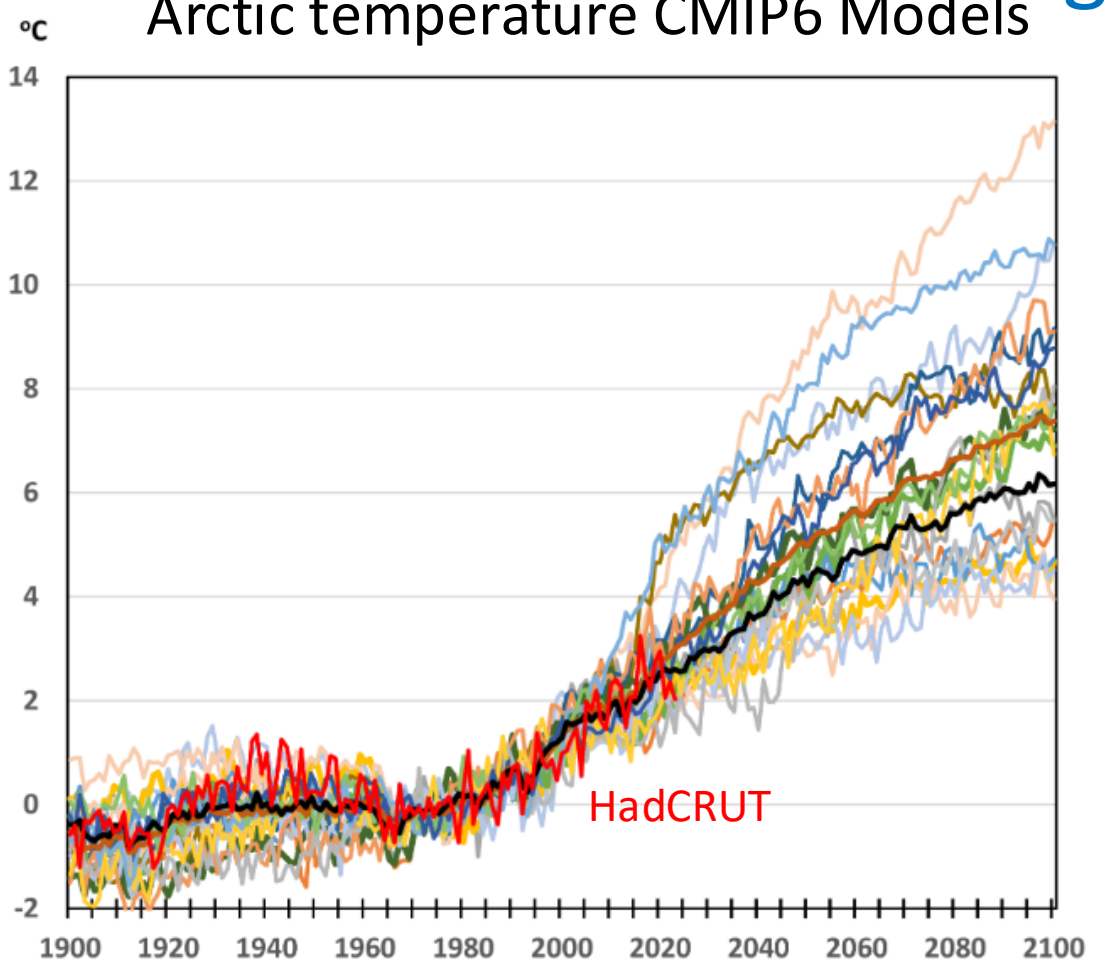
Perovich and Polashenski 2012





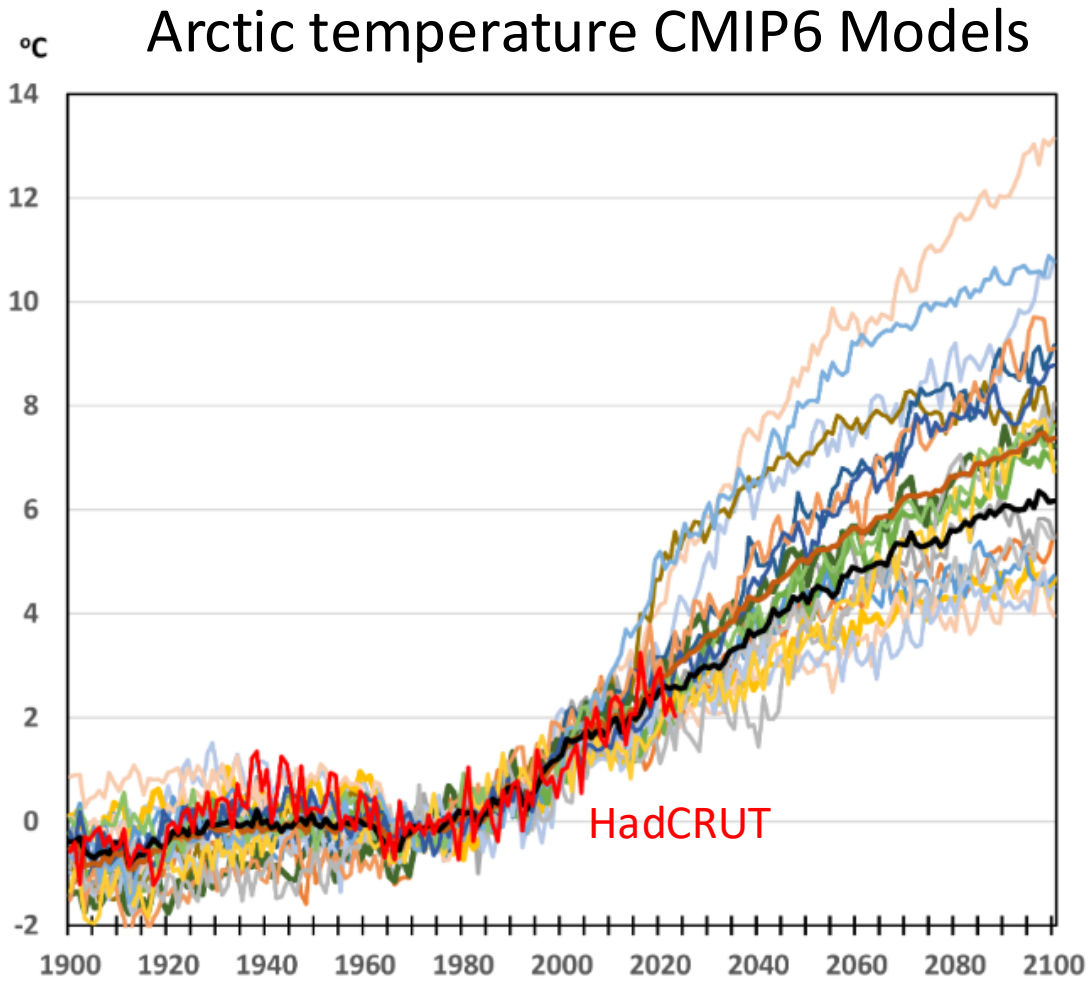


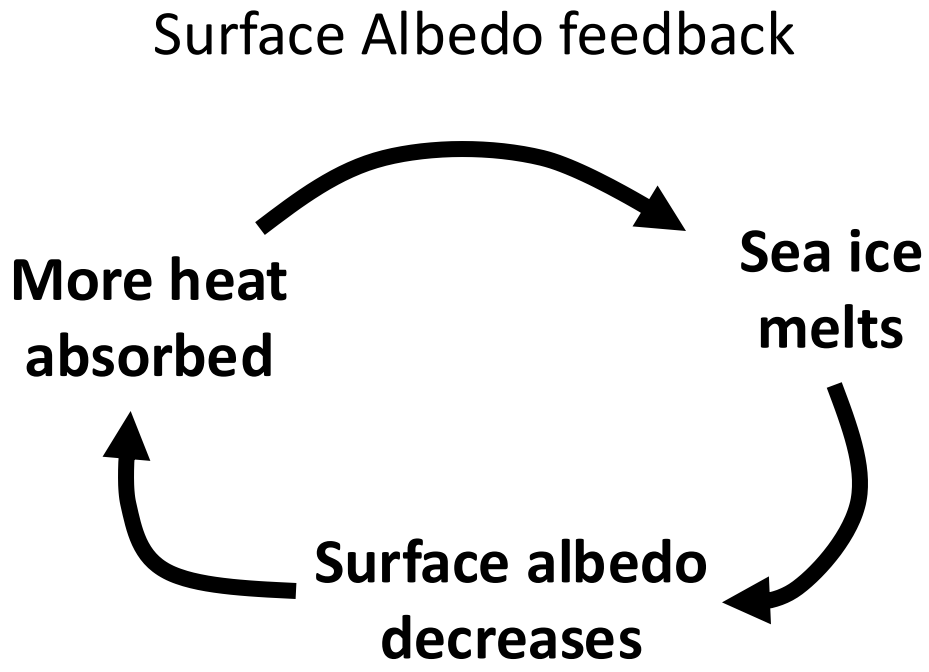
The Arctic is warming nearly four times faster than the globe



Chylek et al. 2024

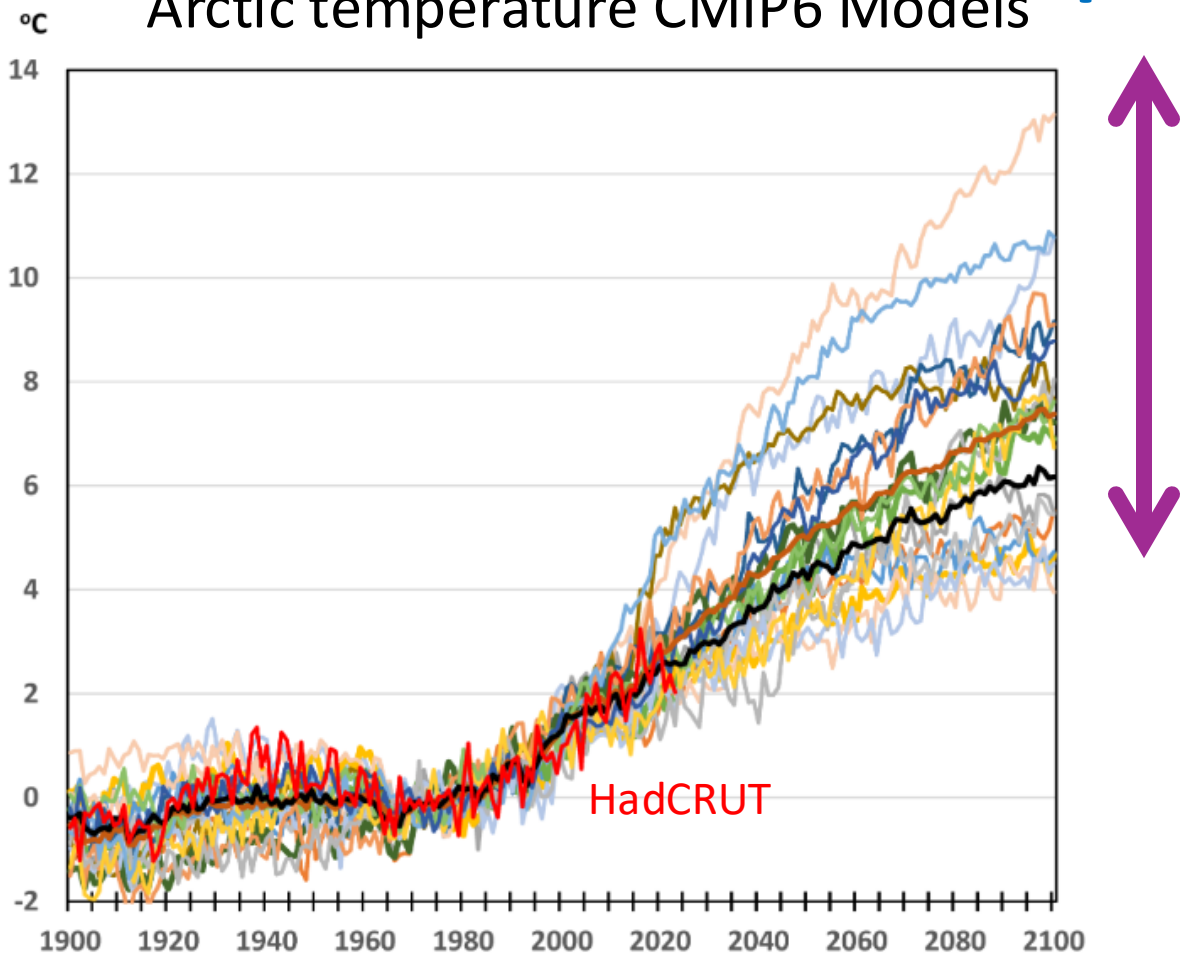
The surface ice-albedo feedback is widely accepted to play a leading role on Arctic warming





Chylek et al. 2024

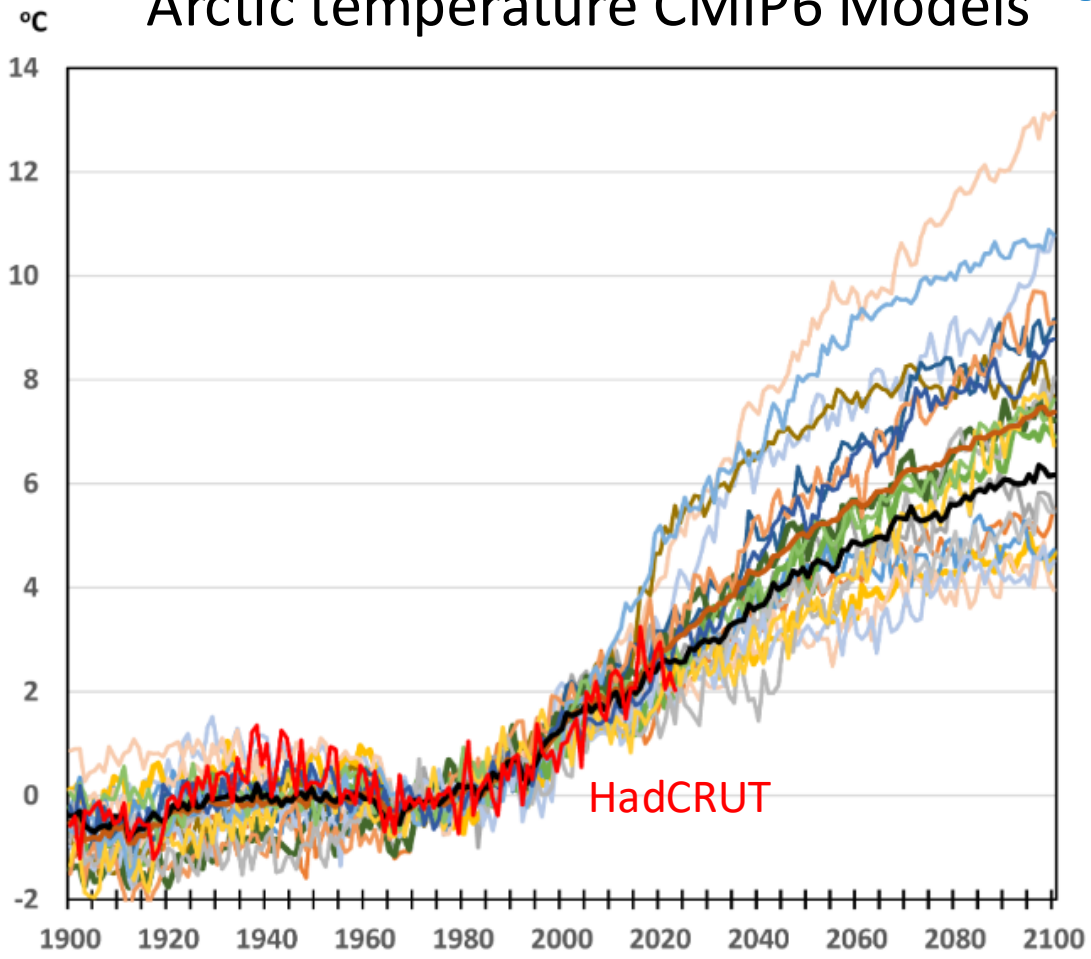
The albedo feedback contributes most to **inter-model spread**



Chylek et al. 2024

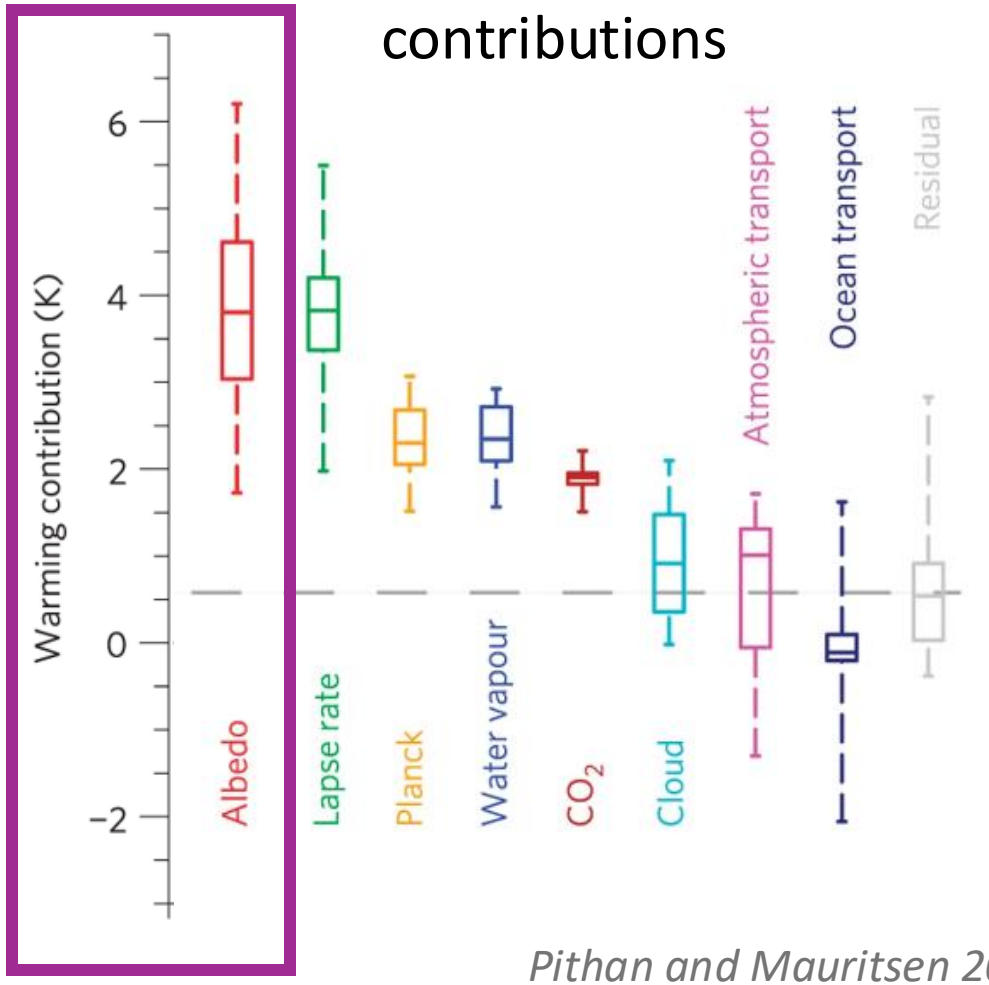
The albedo feedback contributes most to **inter-model spread**

Arctic temperature CMIP6 Models



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

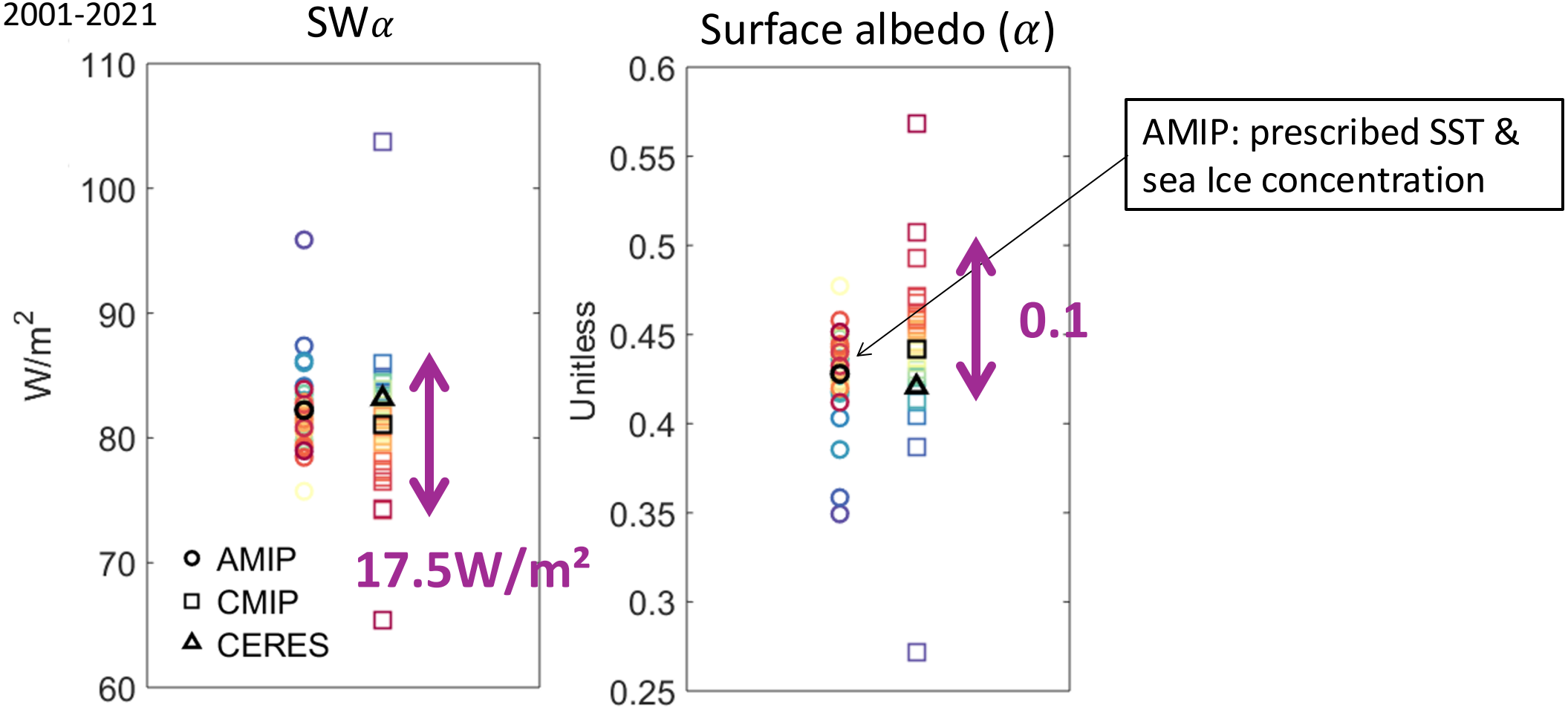
- CERES EBAF Ed4.1 product : 2001-2021
- AMIP 32 models: historical run, 1980-2014 (SST & SIC fixed)
- CMIP 32 models: historical run, SSP245/585 1980-2100 (Full coupled models)
- Hurrell SST/sea ice consistency criteria applied to merged HadISST & NCEP-0I2
- ERA5 reanalysis: 1980-2021

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

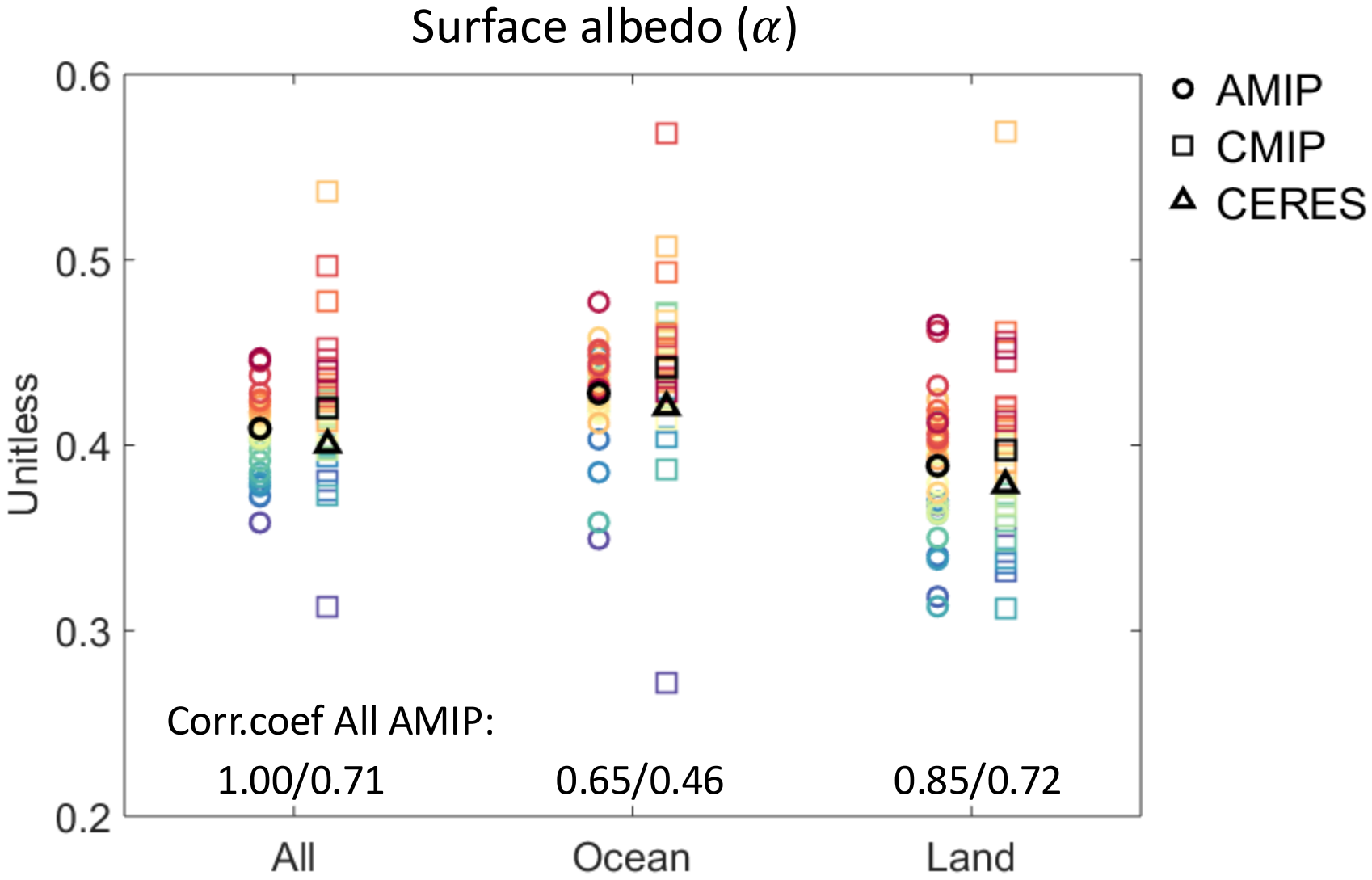
averaged over 65°N,
sunlight season (Mar through Sep)

Surface Albedo differences significantly impact Arctic surface **SW radiation budget**

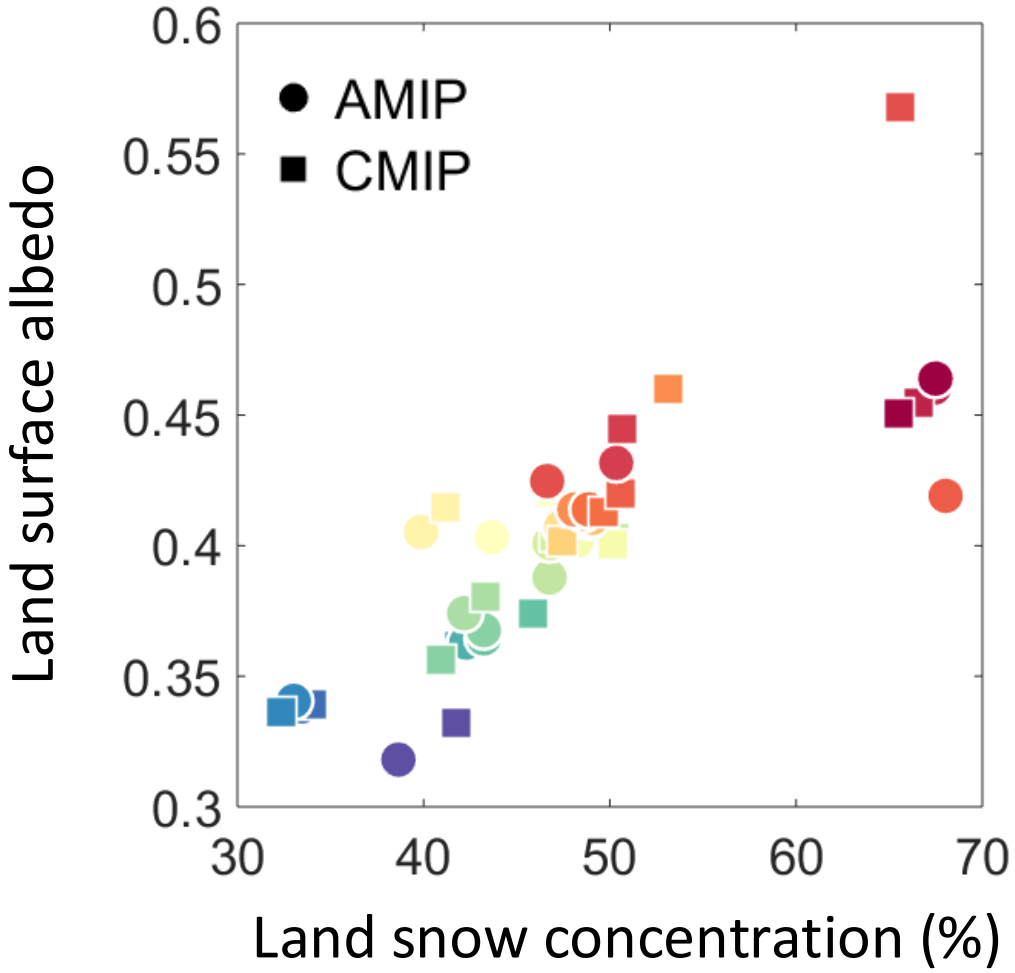
*Present-day: 2001-2021



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



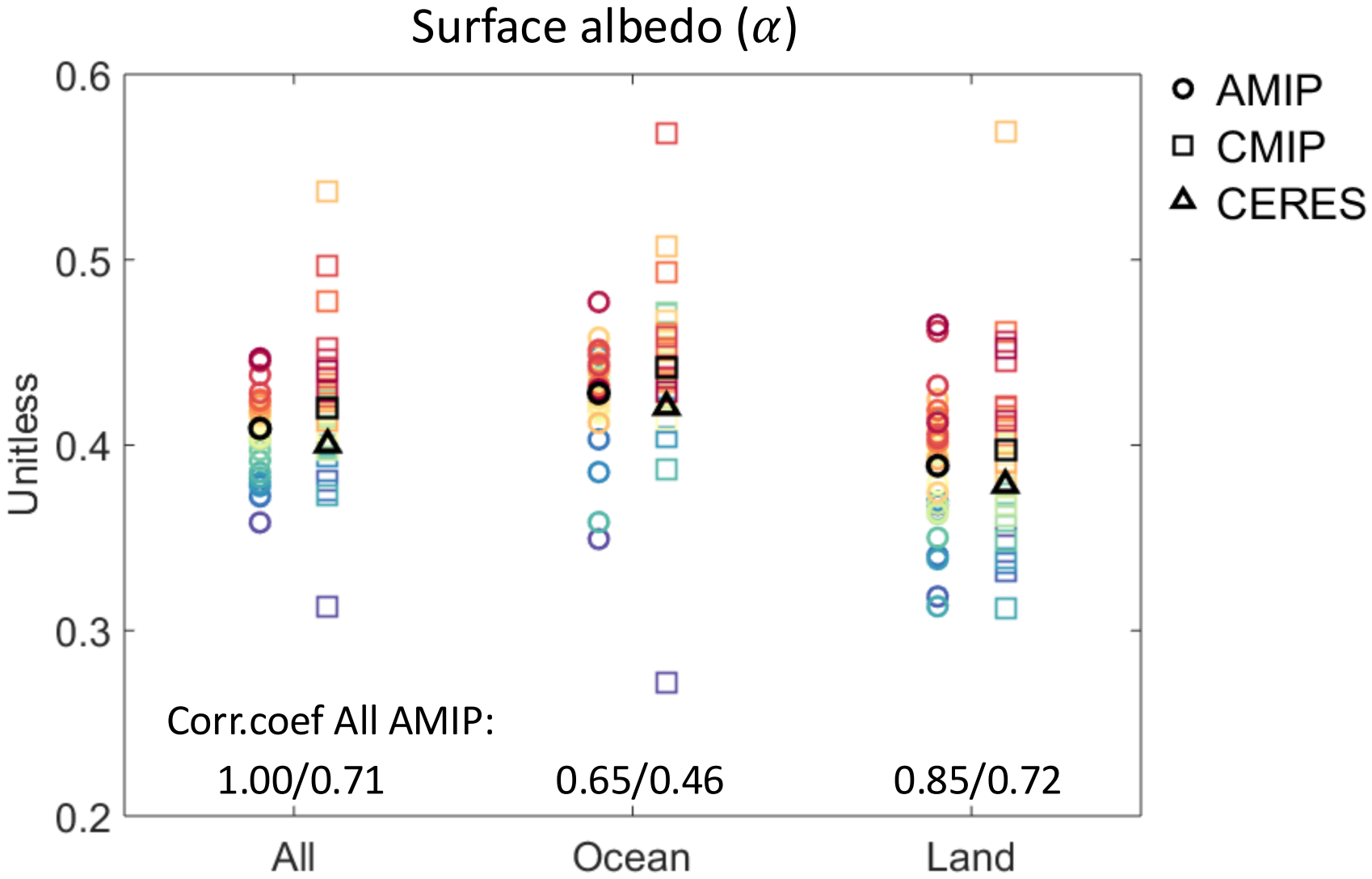
Models with **a larger land snow concentration** exhibit the **higher surface albedo**



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?

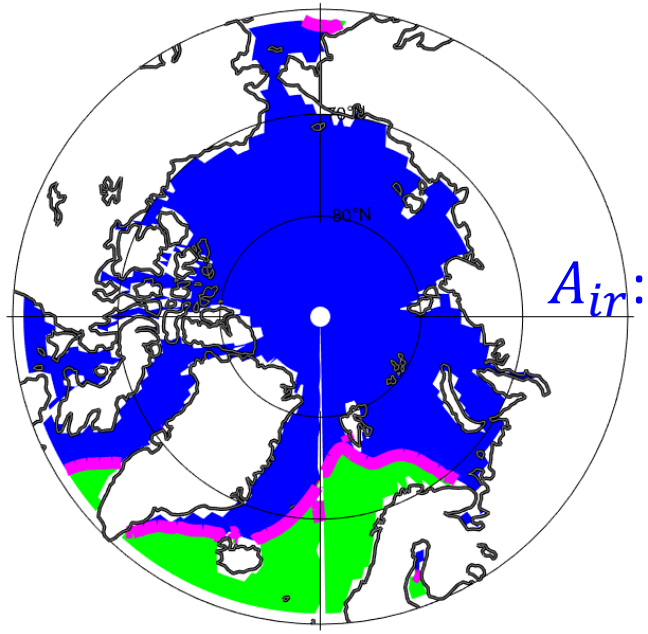


Breaking down albedo: a new definition for ice albedo difference and sea ice concentration difference

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

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

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



A_{ir}: Ice region

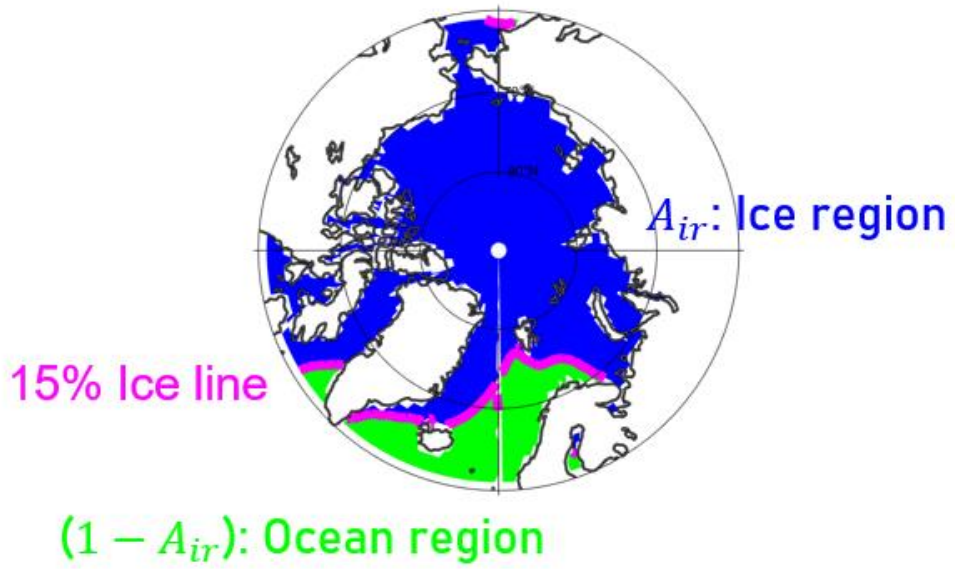
15% sea ice concentration line

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

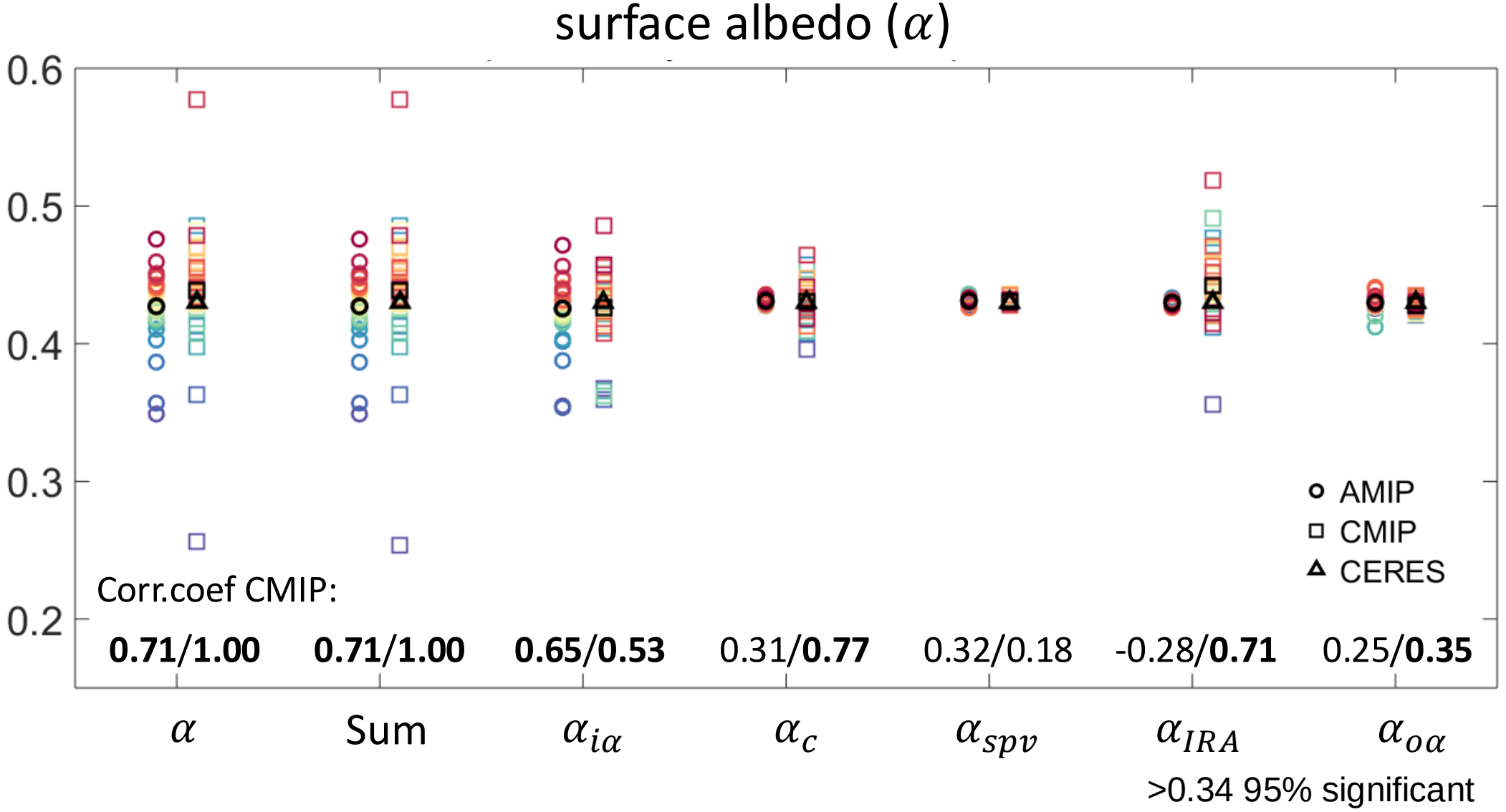
Breaking down albedo: a new definition for ice albedo difference and sea ice concentration difference

$$\delta\alpha = \delta\alpha_{i\alpha} + \delta\alpha_c + \delta\alpha_{spv} + \delta\alpha_{IRA} + \delta\alpha_{o\alpha}$$
$$\text{①} \quad \text{②} \quad \text{③} \quad \text{④} \quad \text{⑤}$$

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



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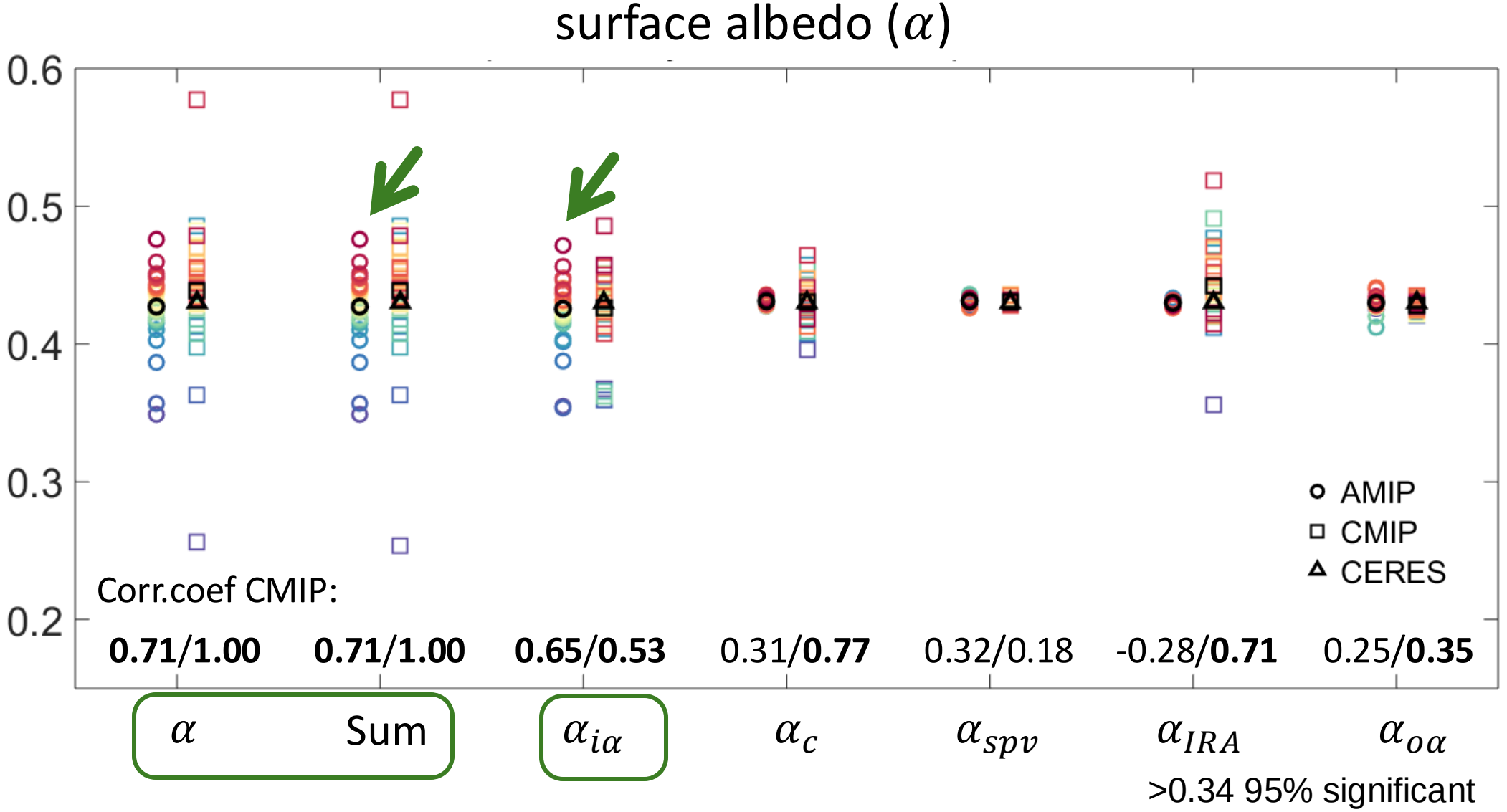

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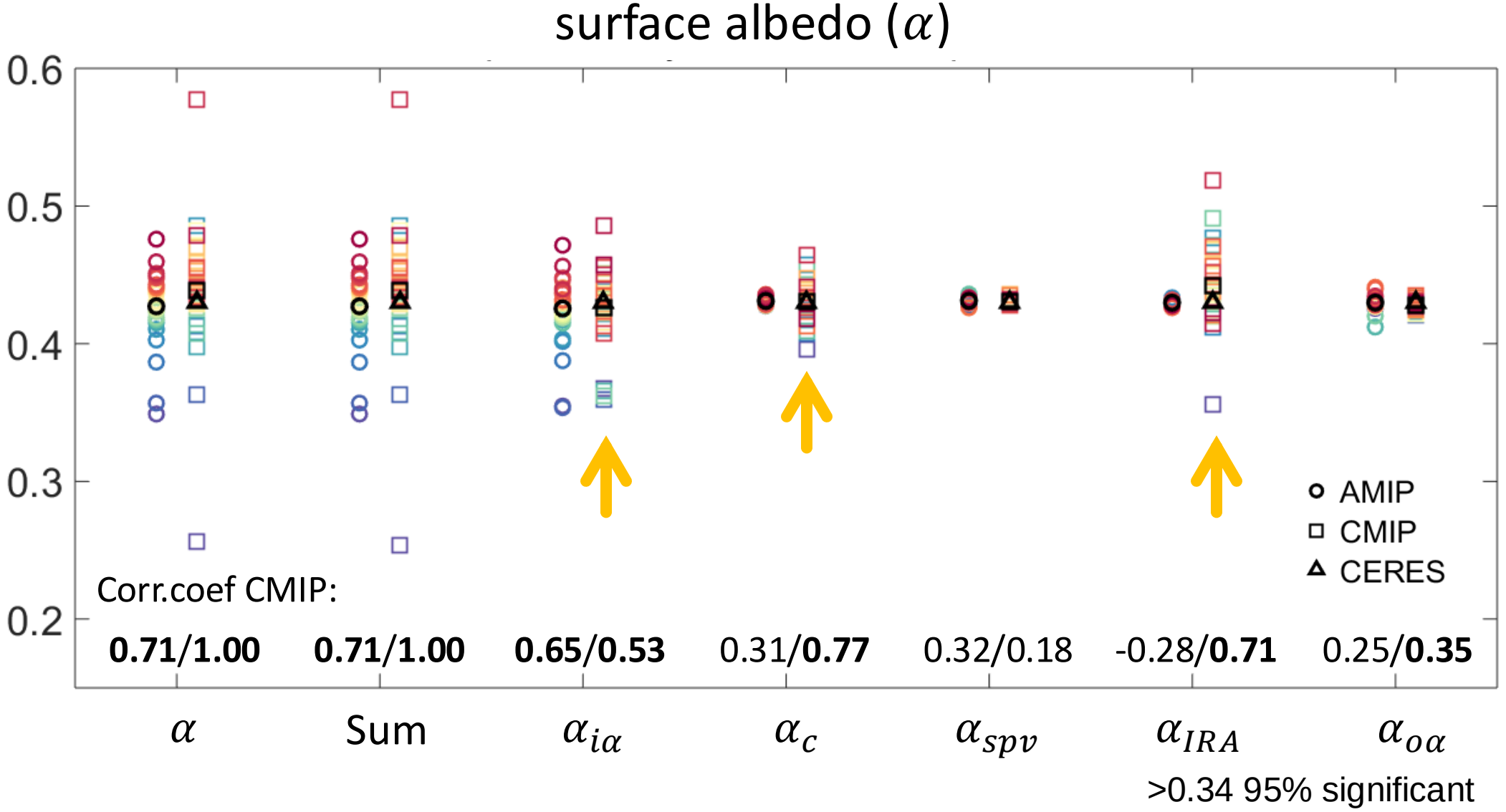
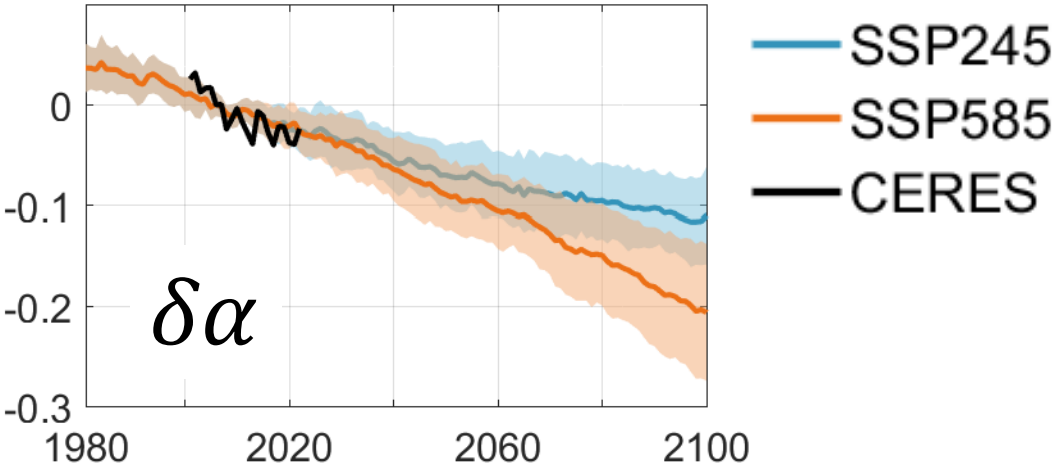
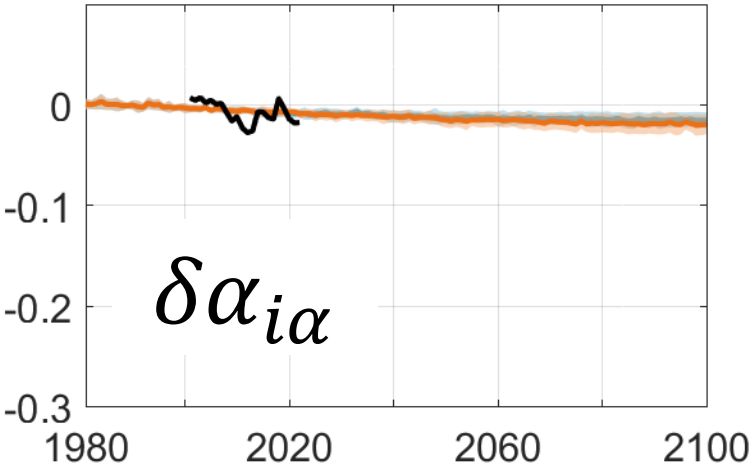
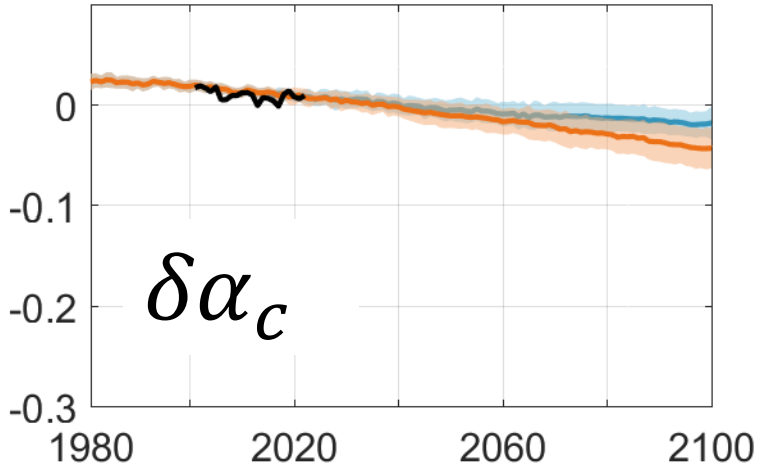


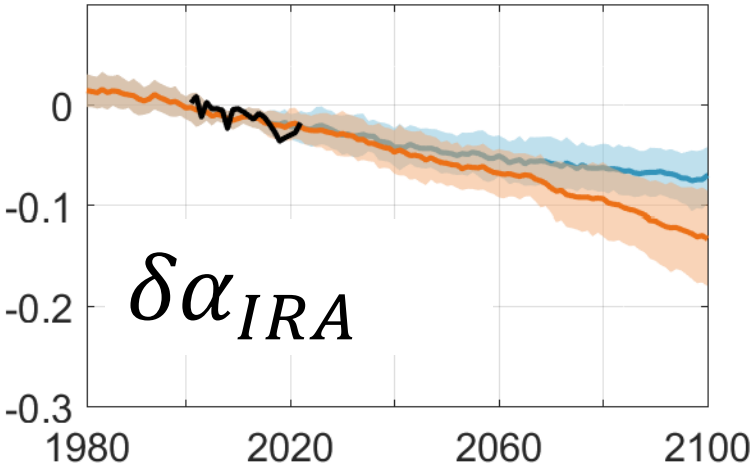
The temporal evolution of surface albedo changes closely follows the ice region term



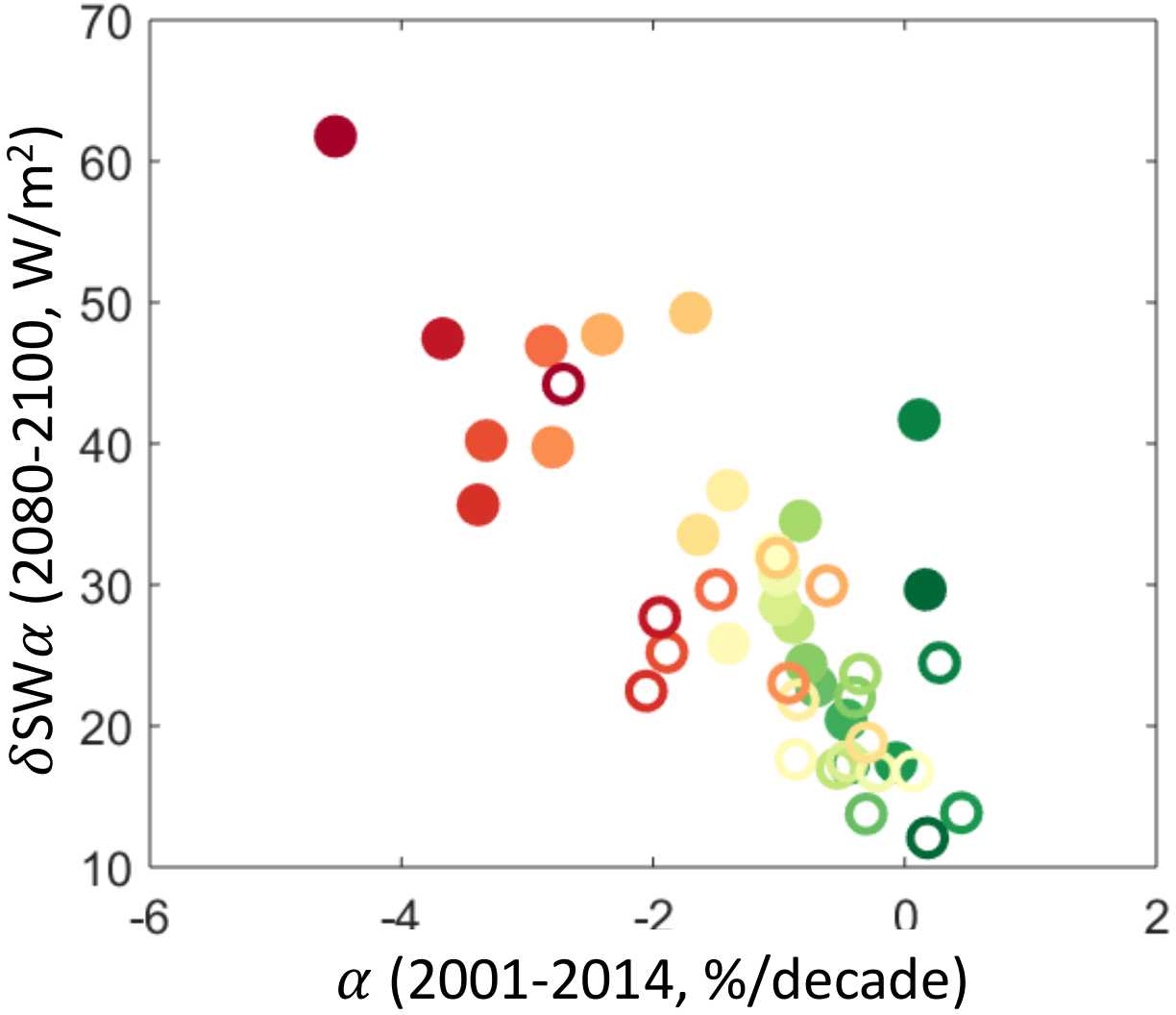
- CERES shows a sharp decline in trend until around 2010, with significant fluctuations affected by the sea ice albedo term
- Minimal variability of the sea ice albedo term in models compared to the considerable interannual variability and significant fluctuations in CERES





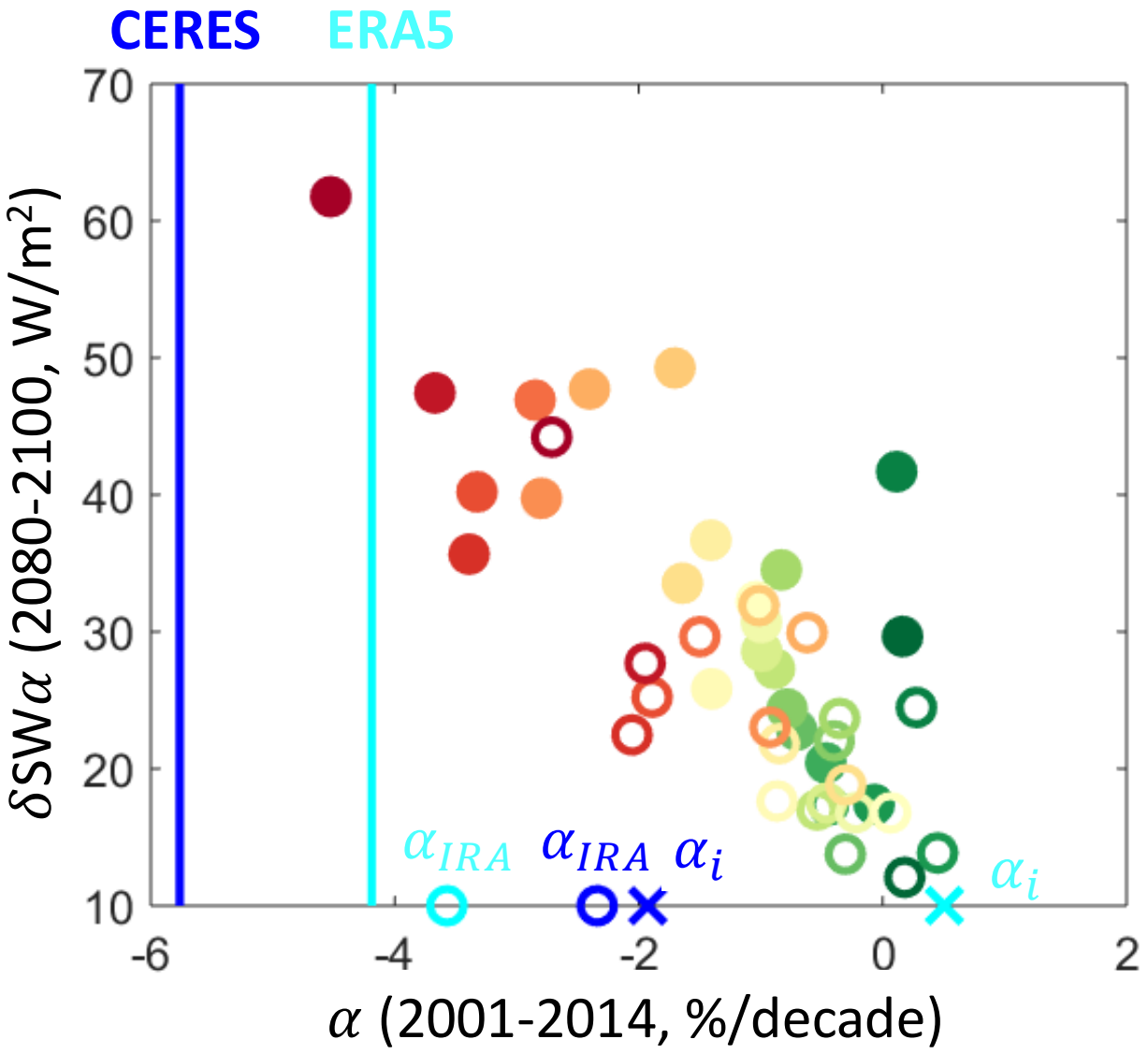


Greater declines in albedo in CMIP models in the present day indicate more future SW changes due to albedo



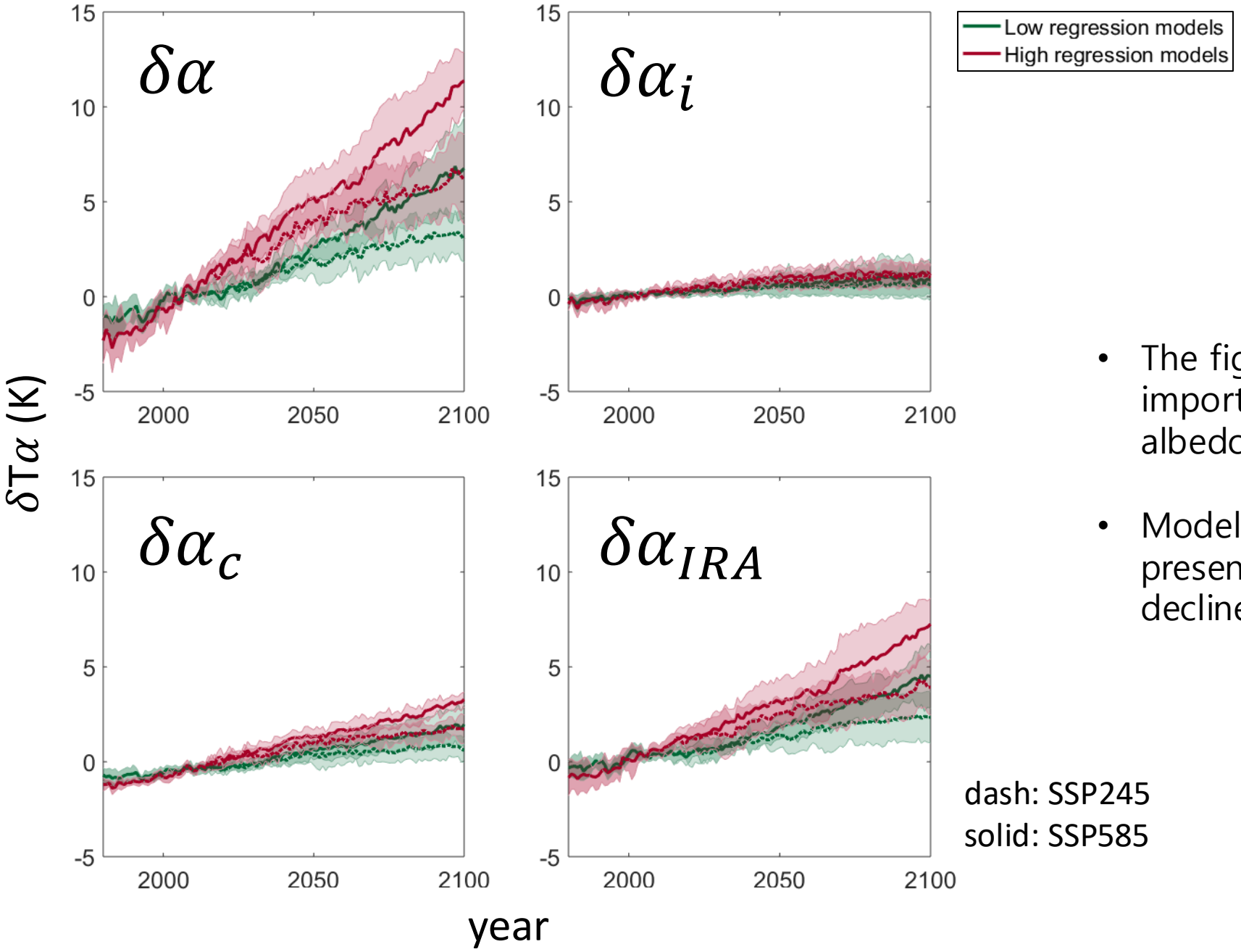
Closed circle: α
Open circle: α_{IRA}

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



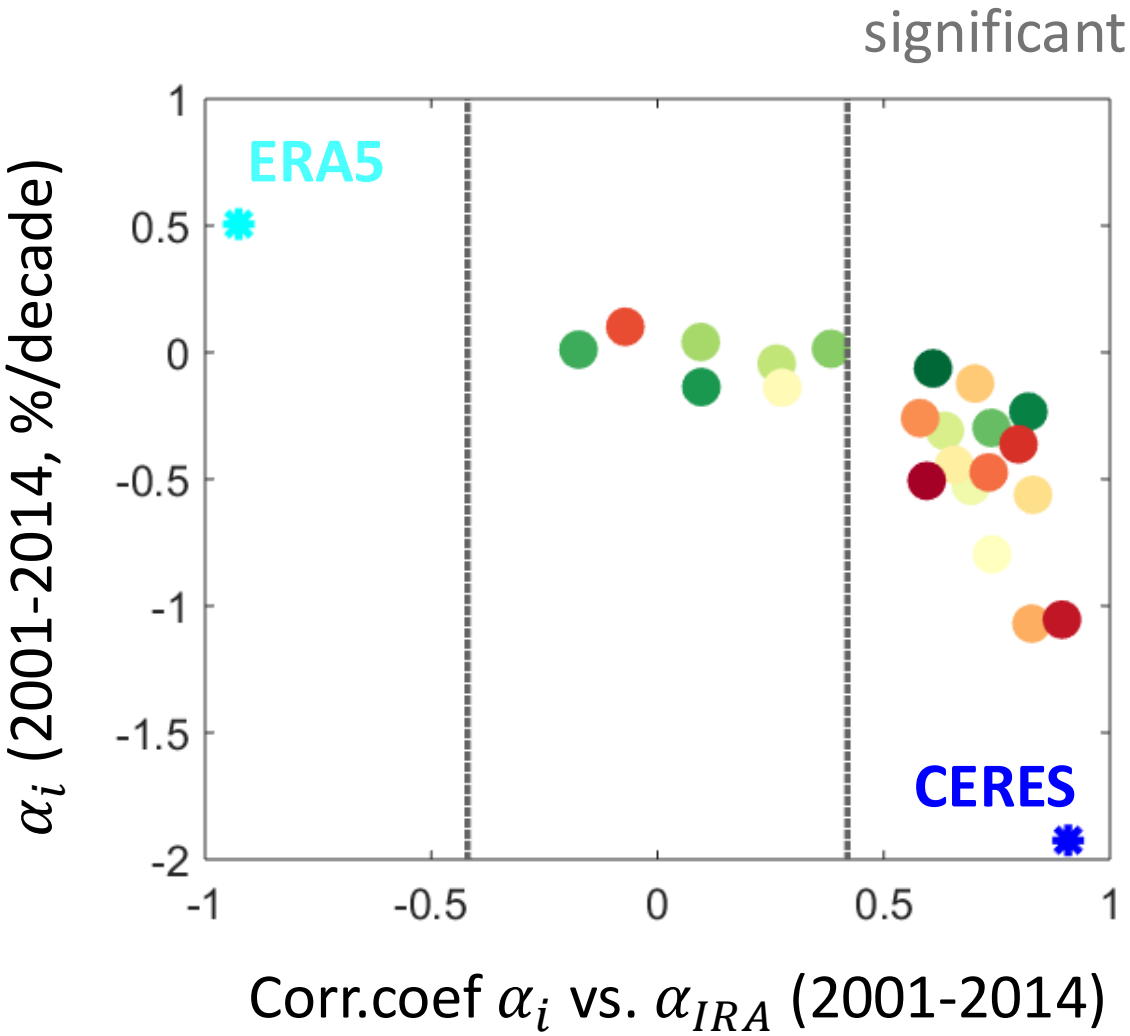
- Present-day declines in models are smaller compared to CERES and ERA5.
- In CERES, the decline in albedo is driven by both the ice region and ice albedo terms.
- However, ERA5 shows an opposite trend between the ice region and ice albedo terms.
- Hereafter, model n=22

Closed circle: α
Open circle: α_{IRA}



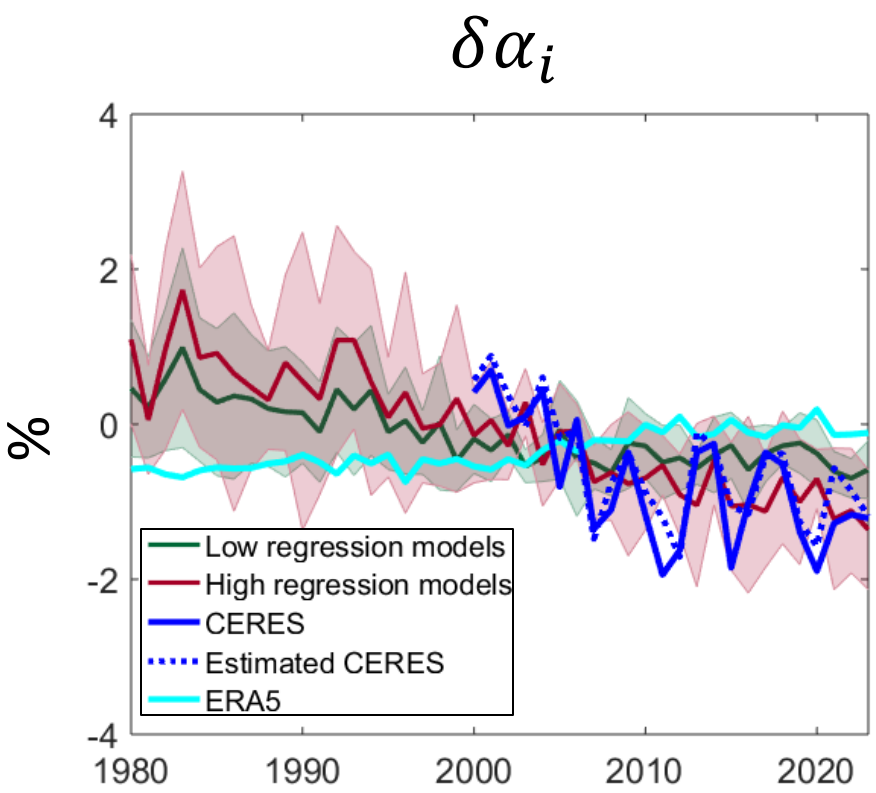
- The figure clearly shows that IRA is an important factor in the decline of albedo in the future.
- Models with greater declines in the present day tend to show larger declines in the future as well.

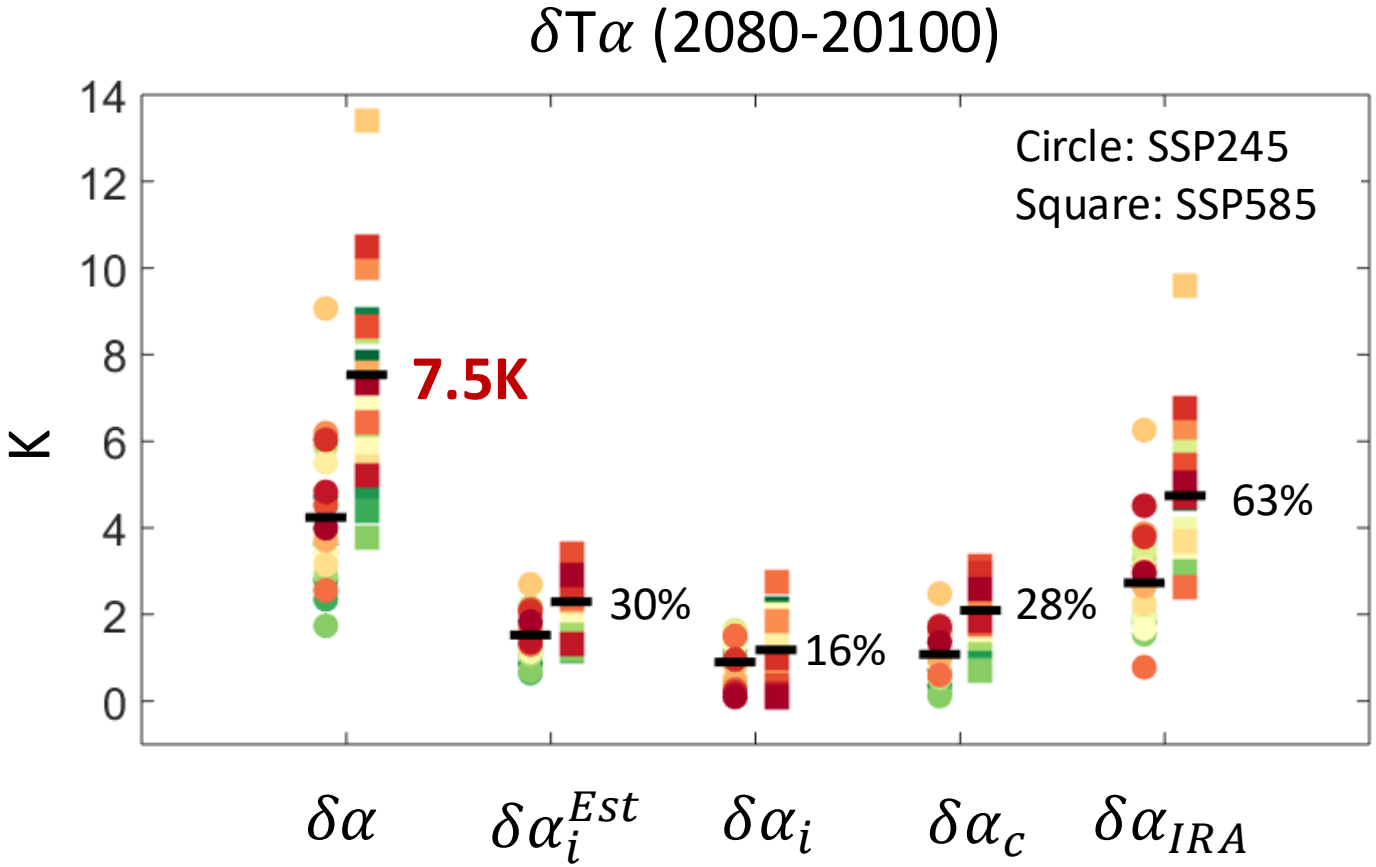
dash: SSP245
solid: SSP585



- CERES shows high correlation between αi and αIRA.
- If there is a strong correlation between αi and αIRA, 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.**

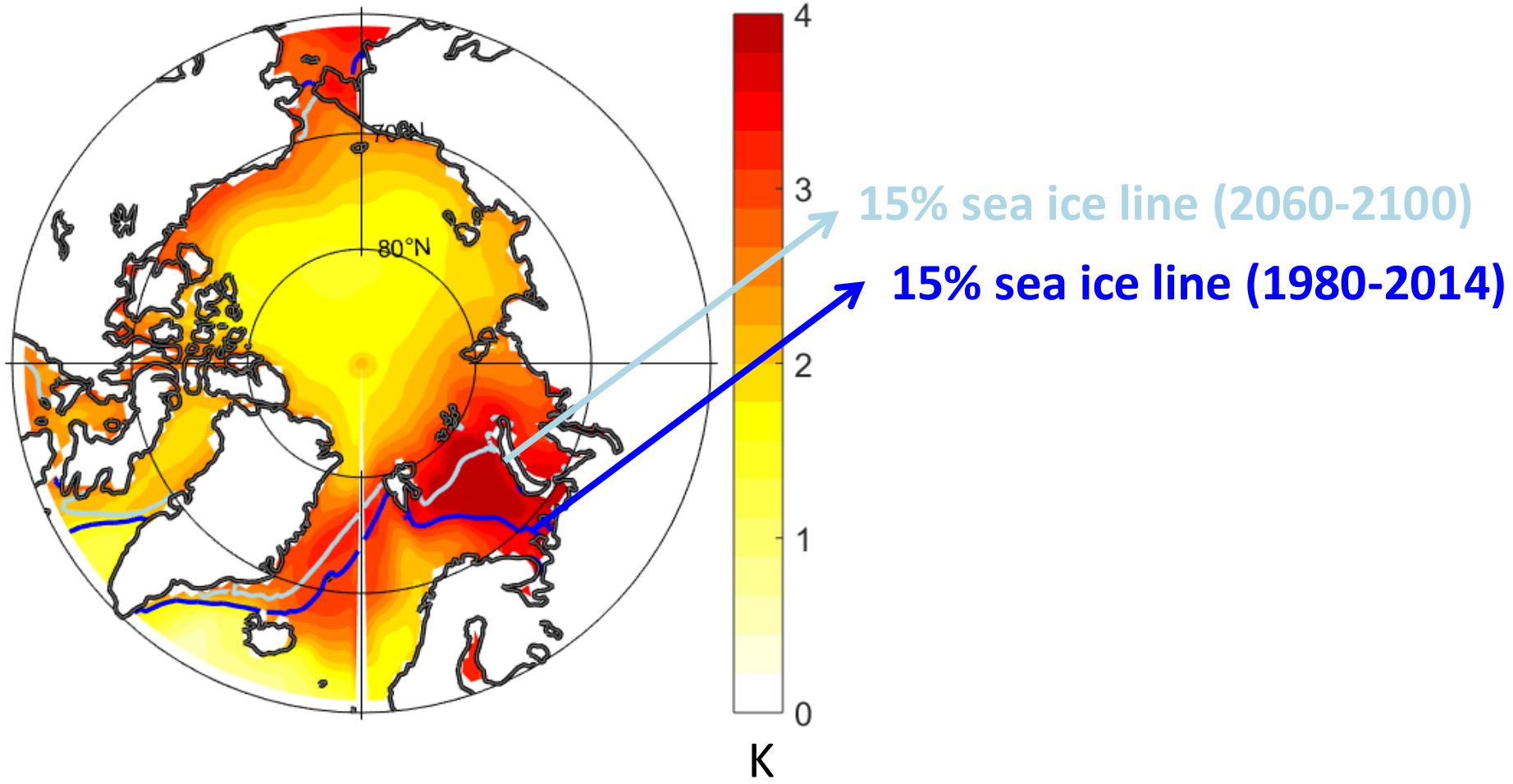
- Between 2000-2021, **CERES data indicates larger variability in the ice albedo term compared to the models.** This suggest that CMIP models might not fully capture the variability in ice albedo, suggesting the potential for greater variability in the near future than current model projections.

Supplementary

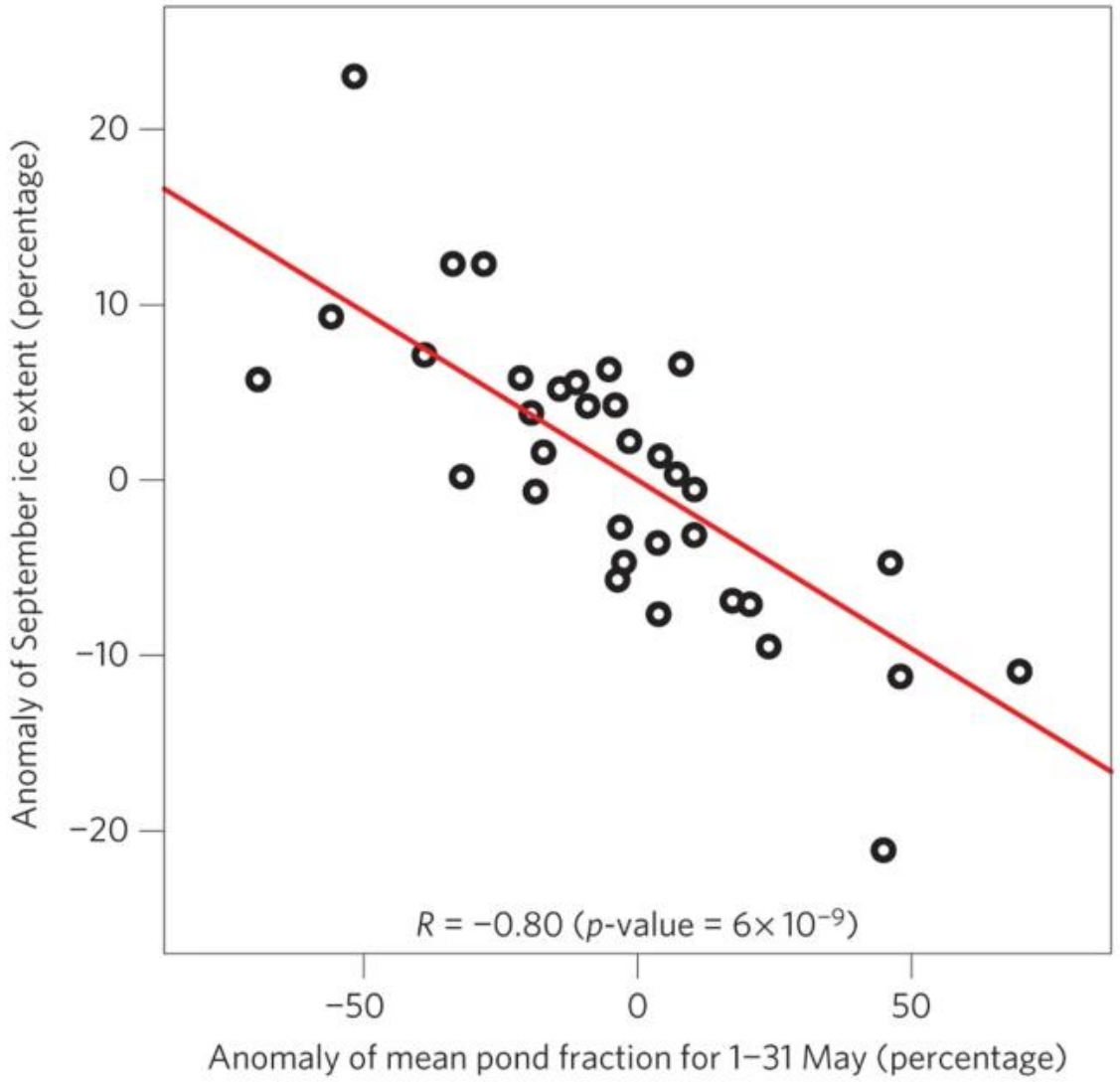
In the future, Ice region term will be important for explaining Arctic warming.

CMIP6 MMM Temperature response

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



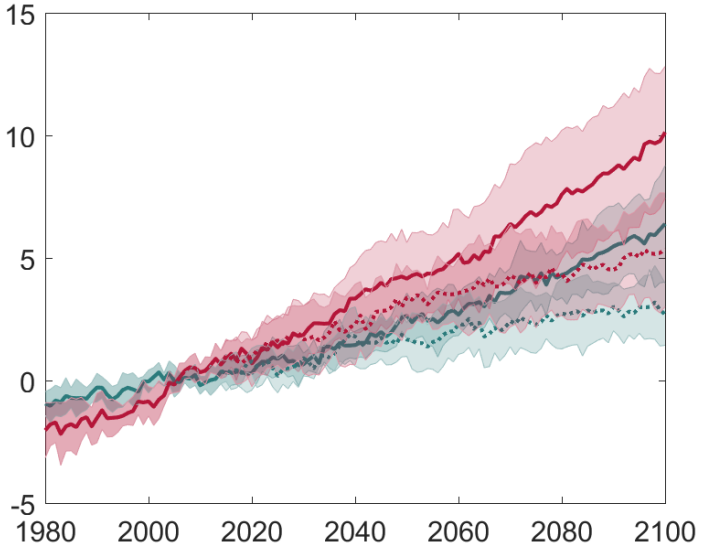
Variability in sea ice albedo has a substantial impact on the evolution of the Arctic climate system



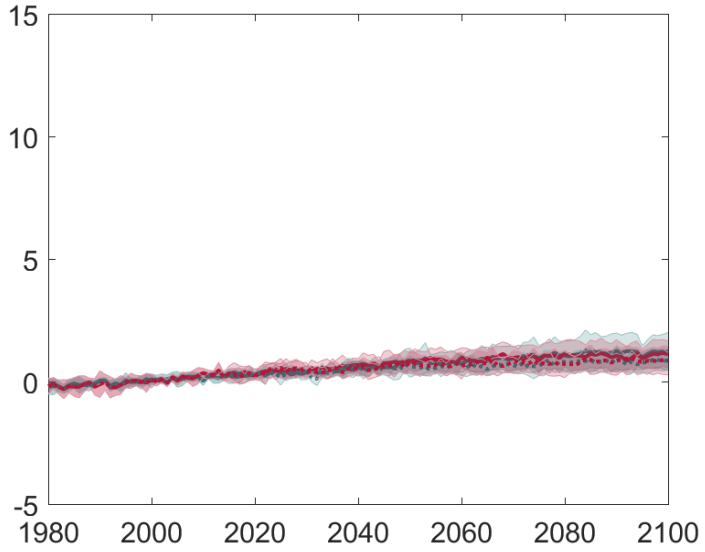
Schroder et al., 2014

Temperature response from Kernel

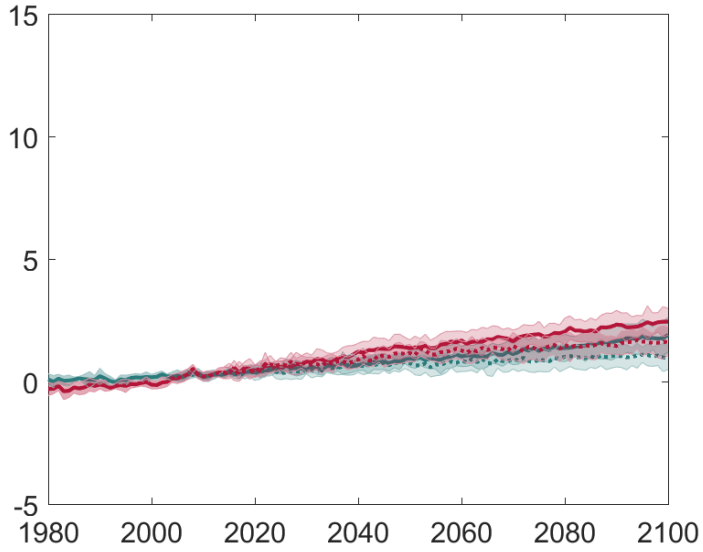
α



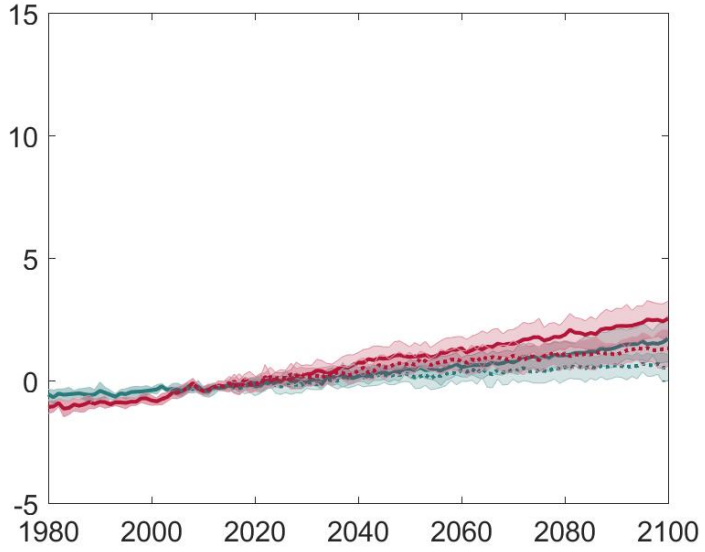
$\alpha_{i\alpha}$



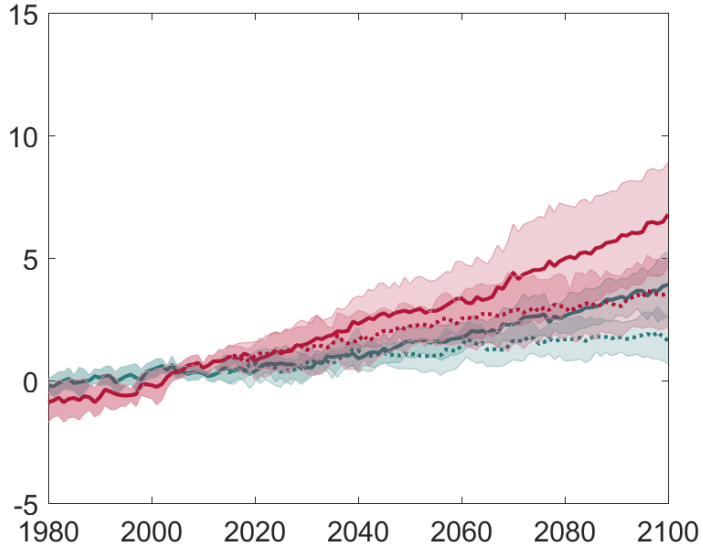
Estimated $\alpha_{i\alpha}$



α_c

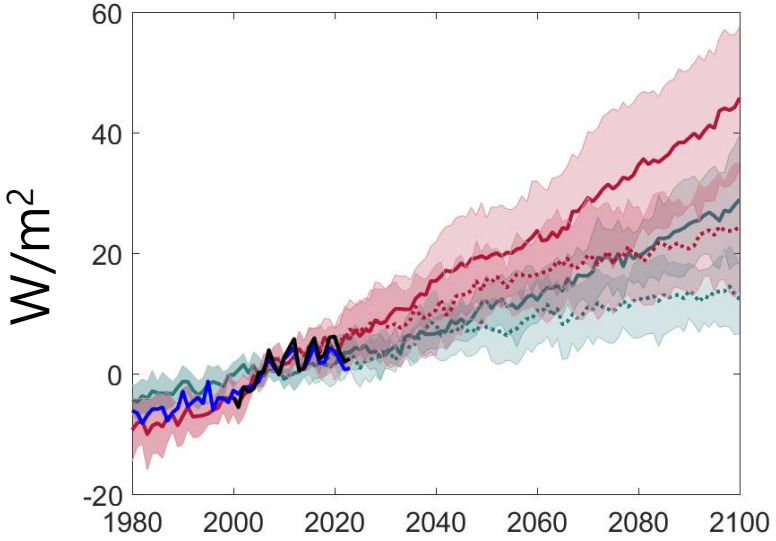


α_{IRA}

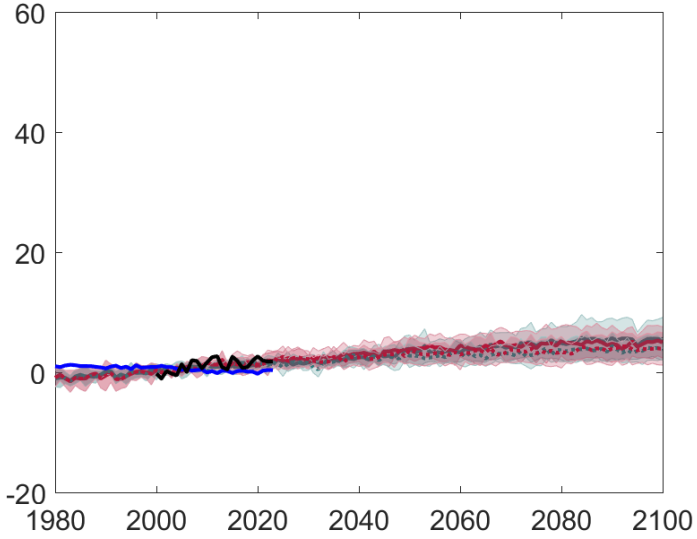


Albedo feedback

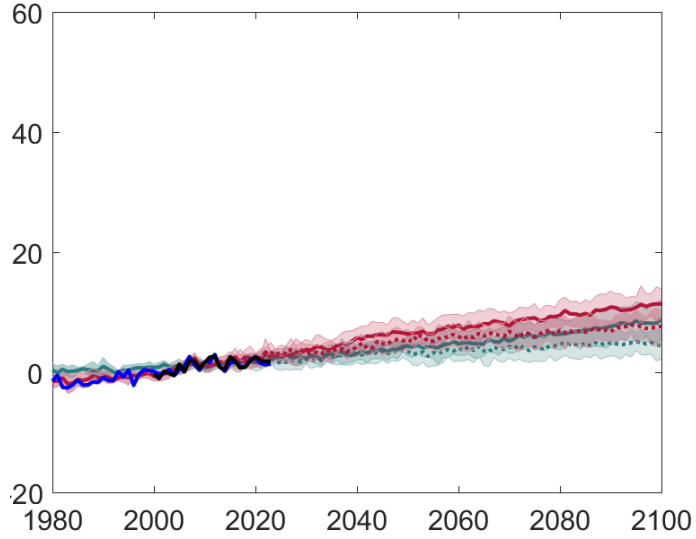
α



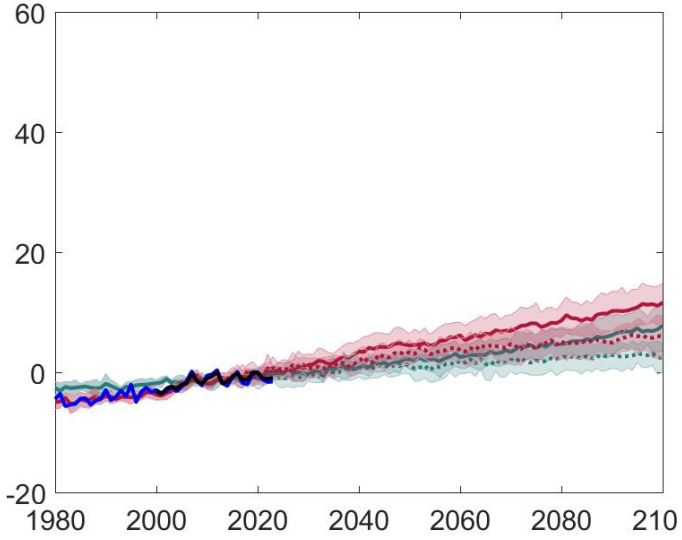
$\alpha_{i\alpha}$



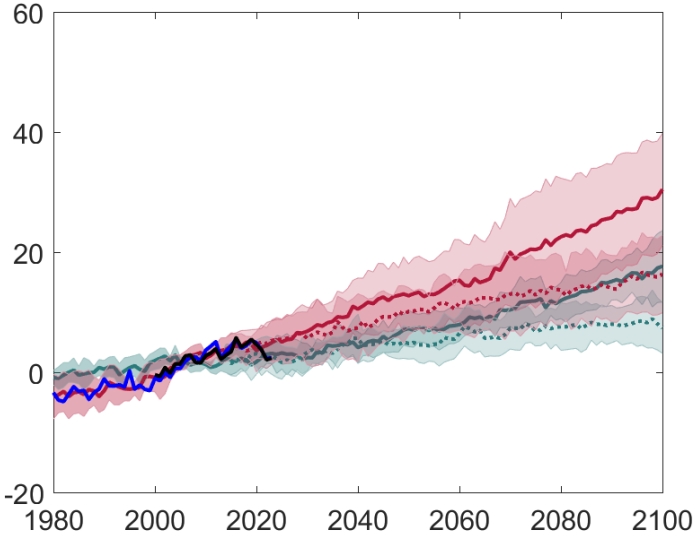
Estimated $\alpha_{i\alpha}$



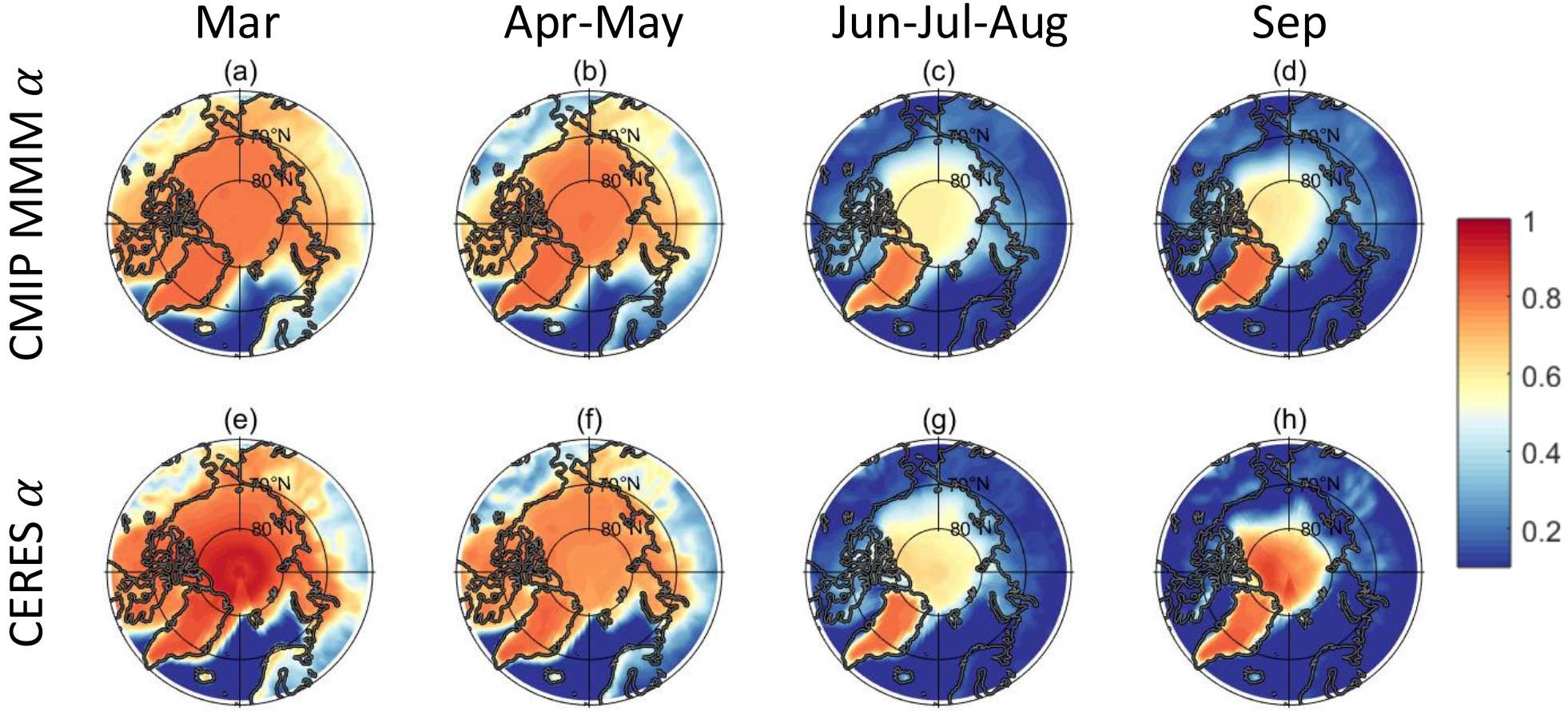
α_c



α_{IRA}



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



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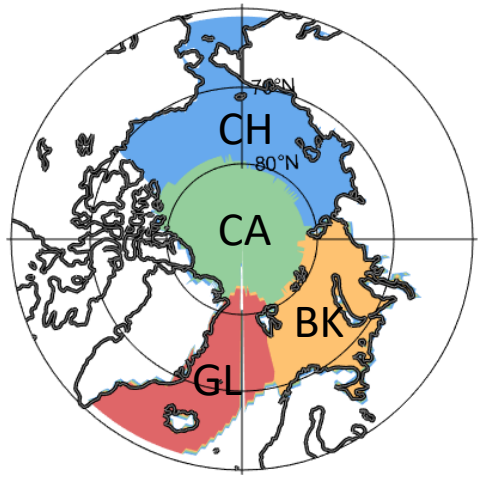
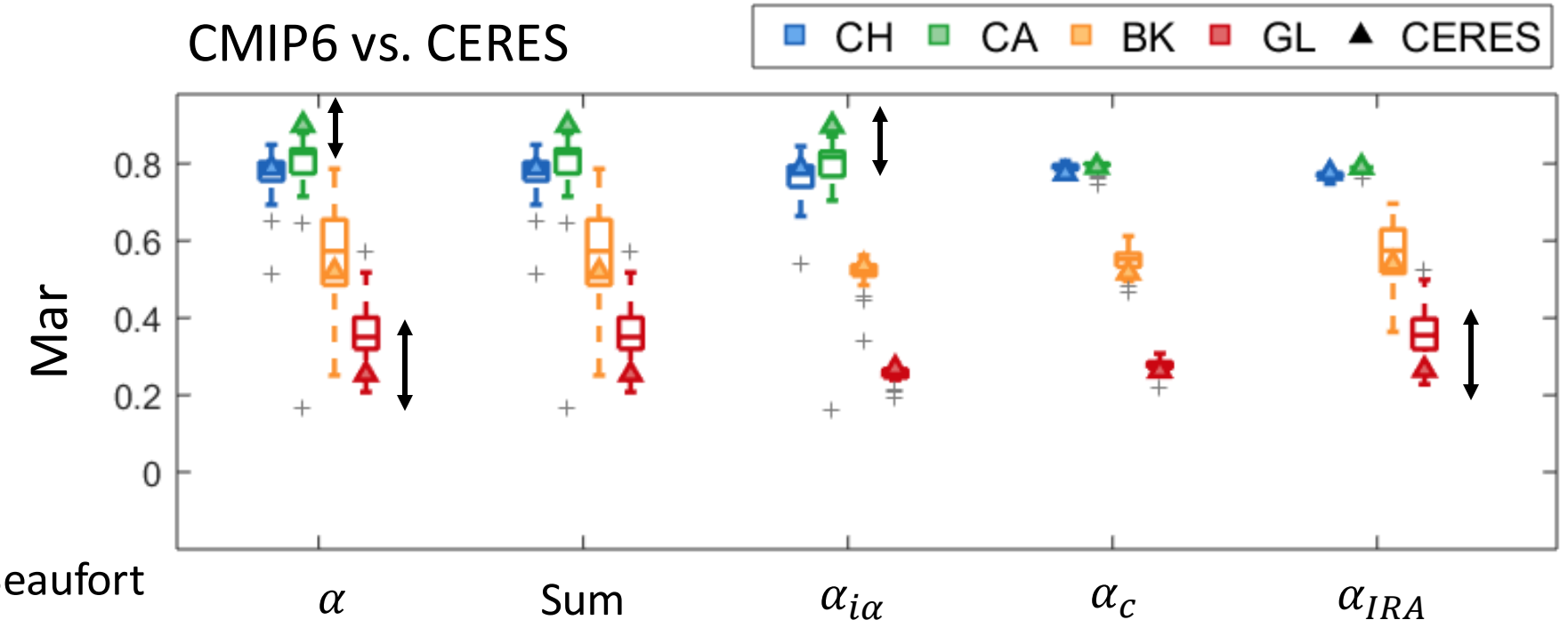


CH: East Siberian, Chukchi, & Beaufort
CA: Central Arctic
BK: Barents, Kara, & Laptev
GL: Greenland sea



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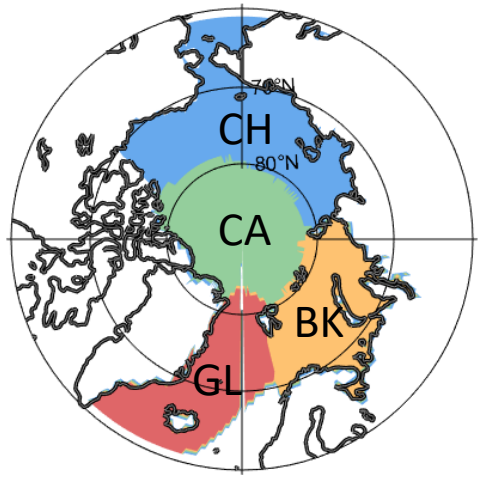

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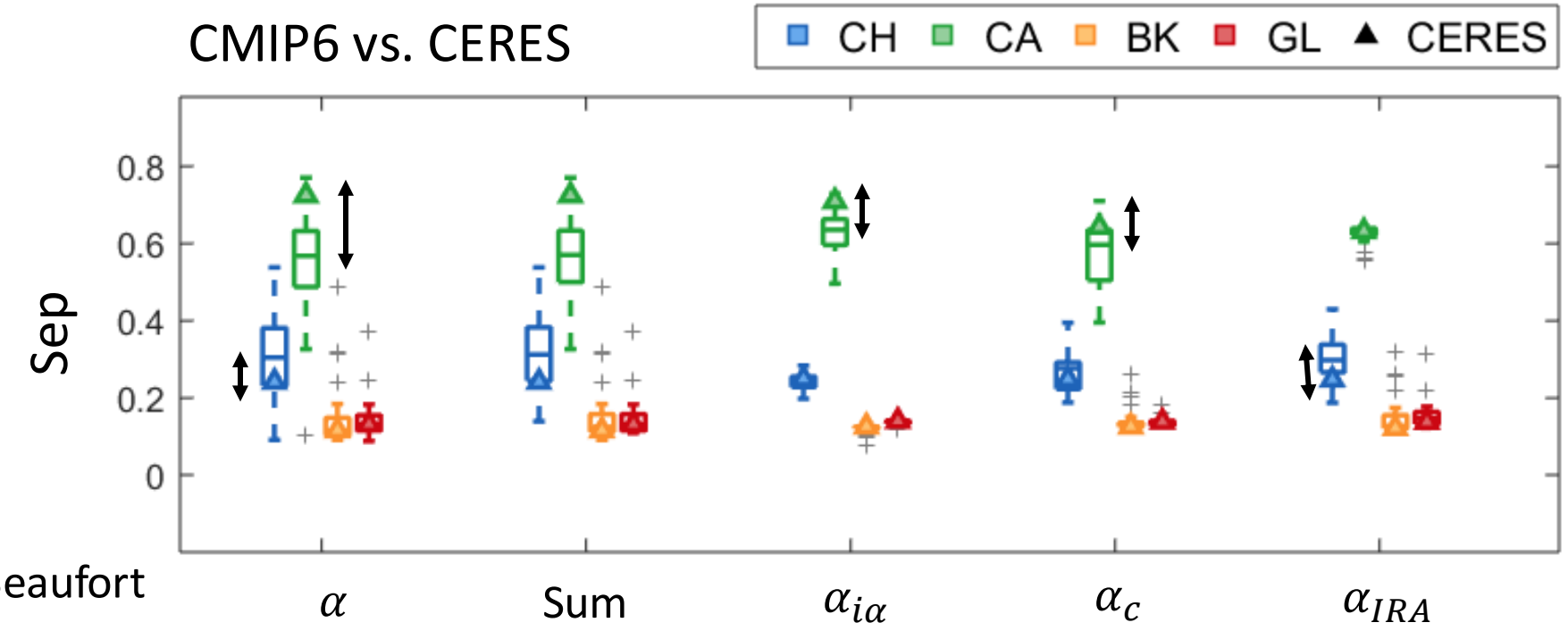
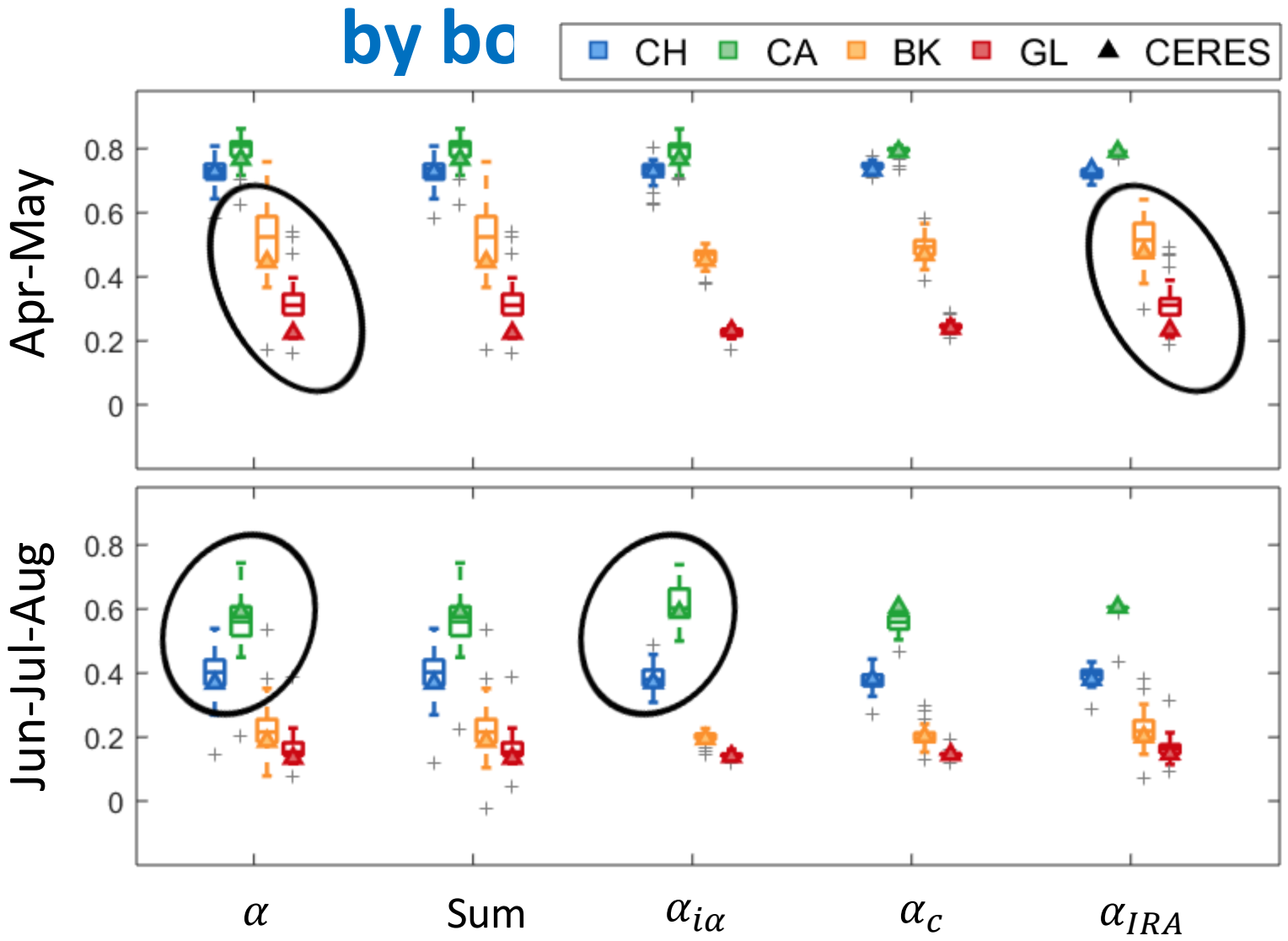
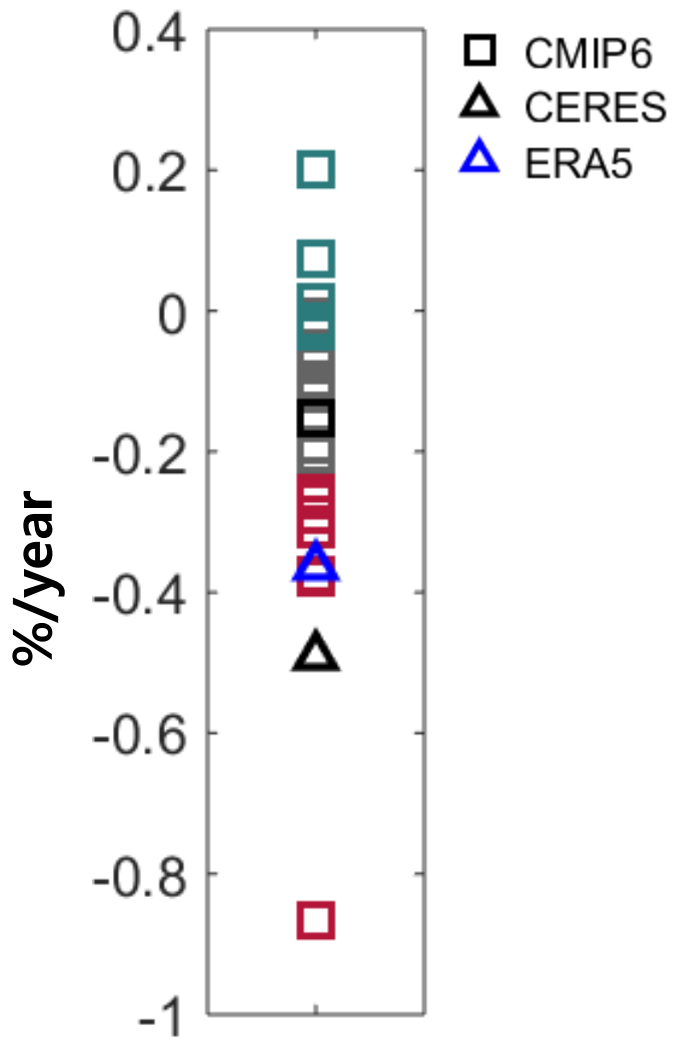


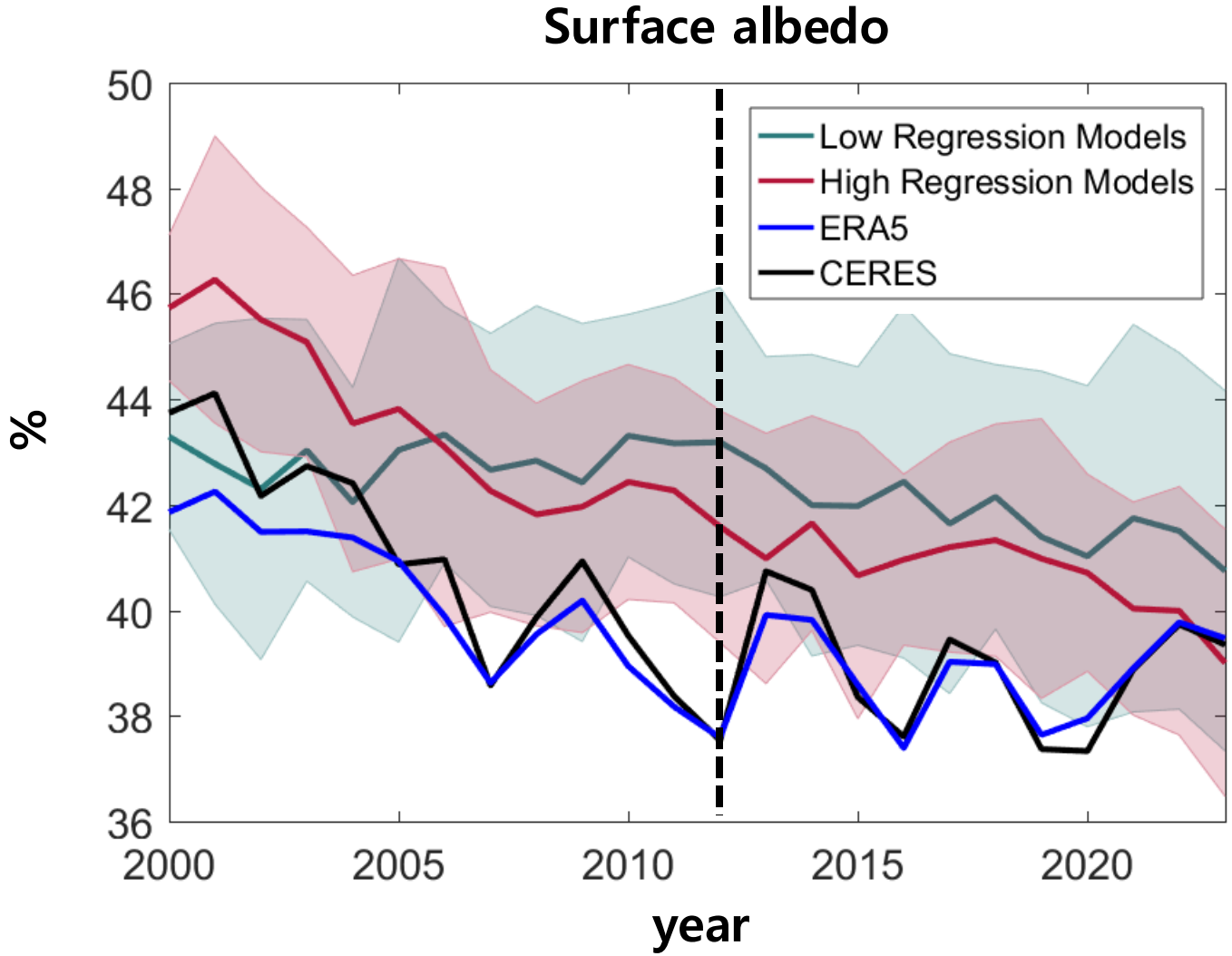
The large spread across CMIP models is significantly influenced by bo variations



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

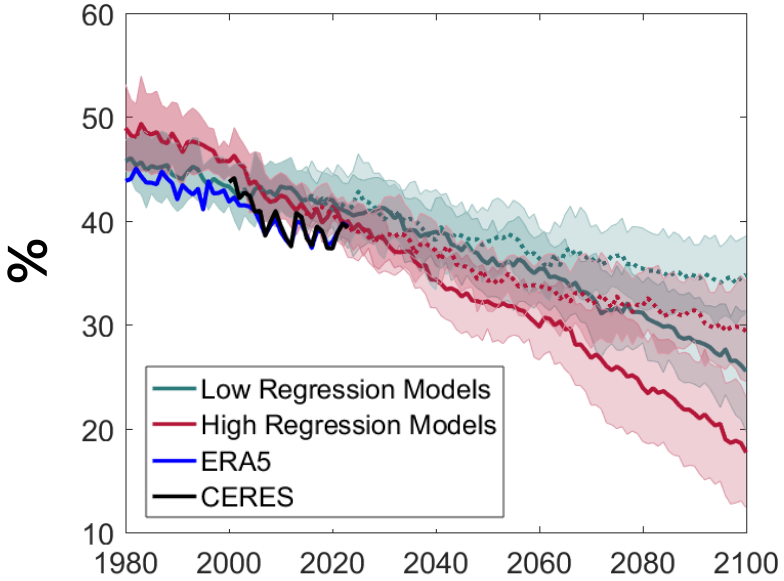
Late summer season:
Ice albedo term contributing to the albedo spread across the CH and CA



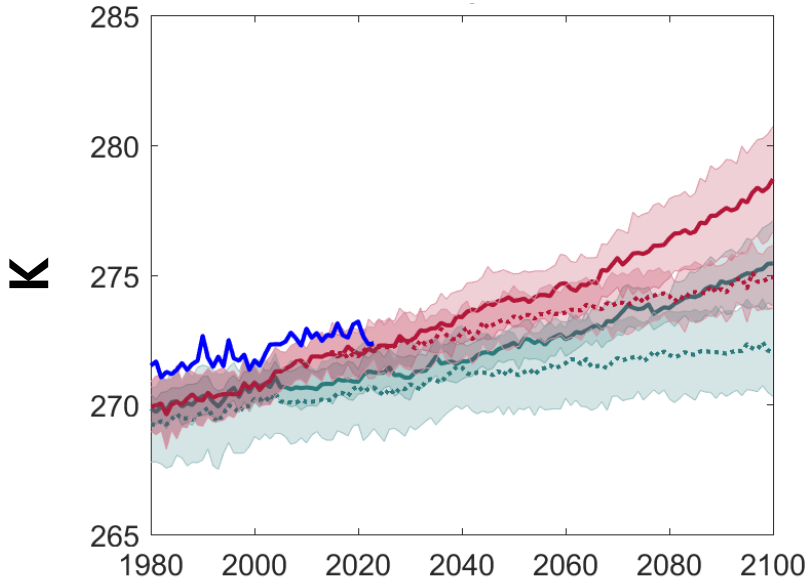


Arctic ocean (Apr-Aug)

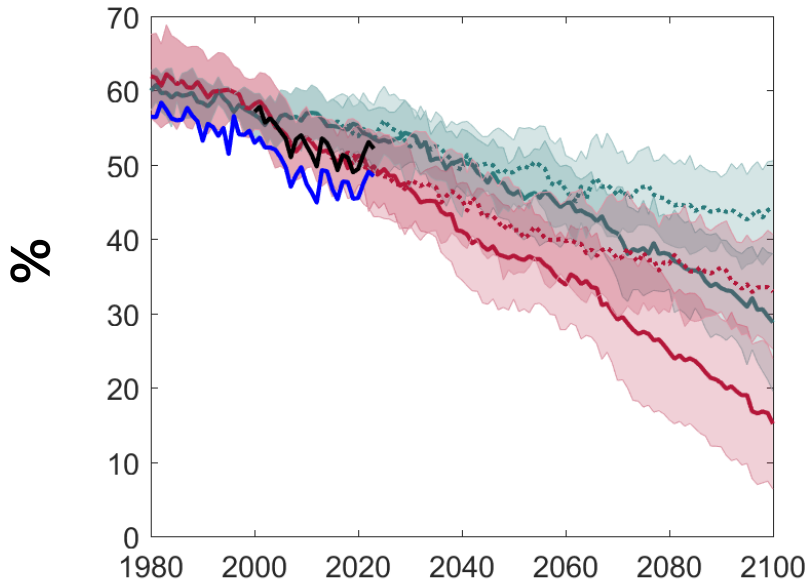
Surface albedo



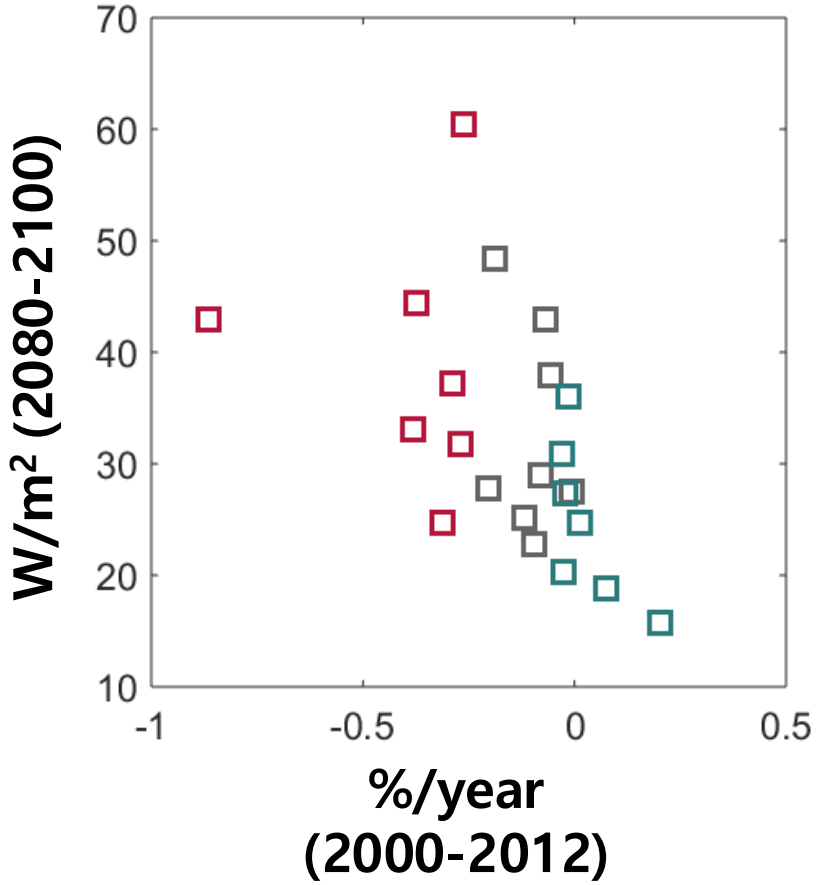
Surface temperature



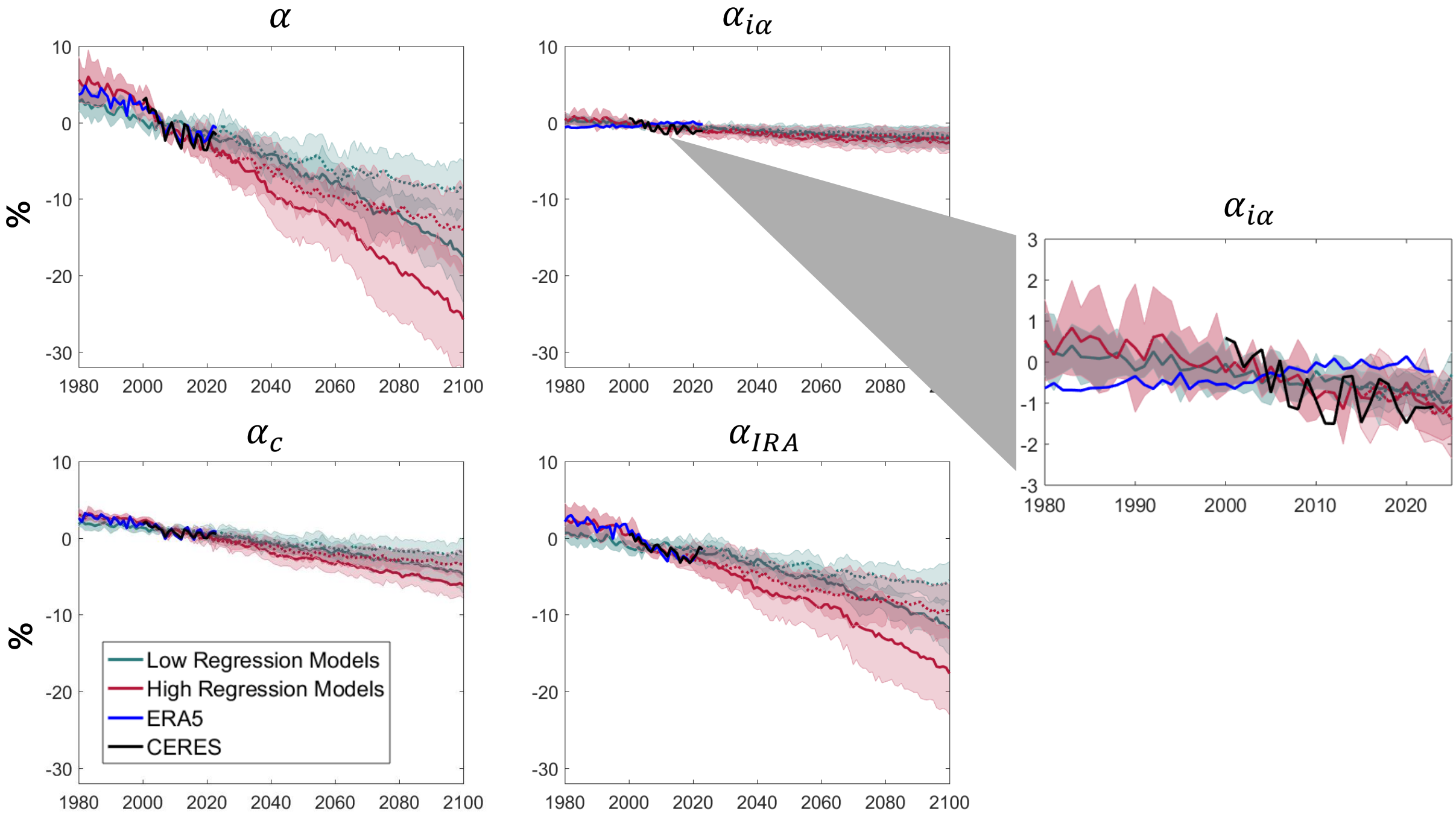
Sea ice concentration



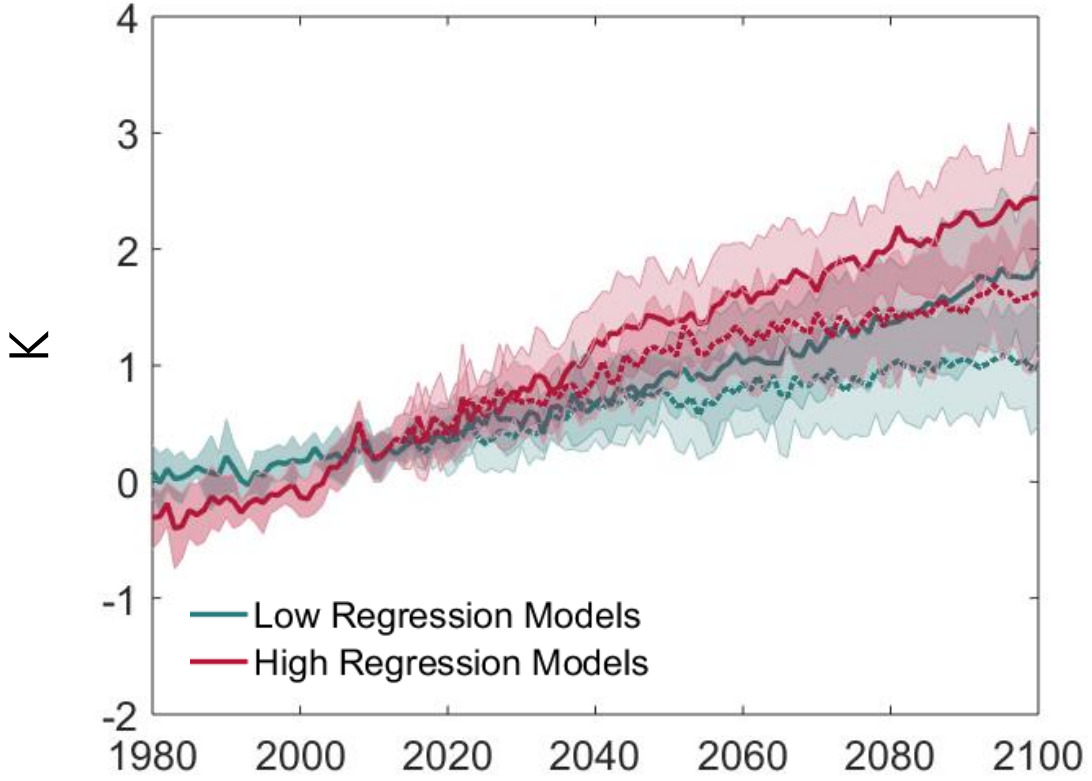
Regression vs. Albedo fbk



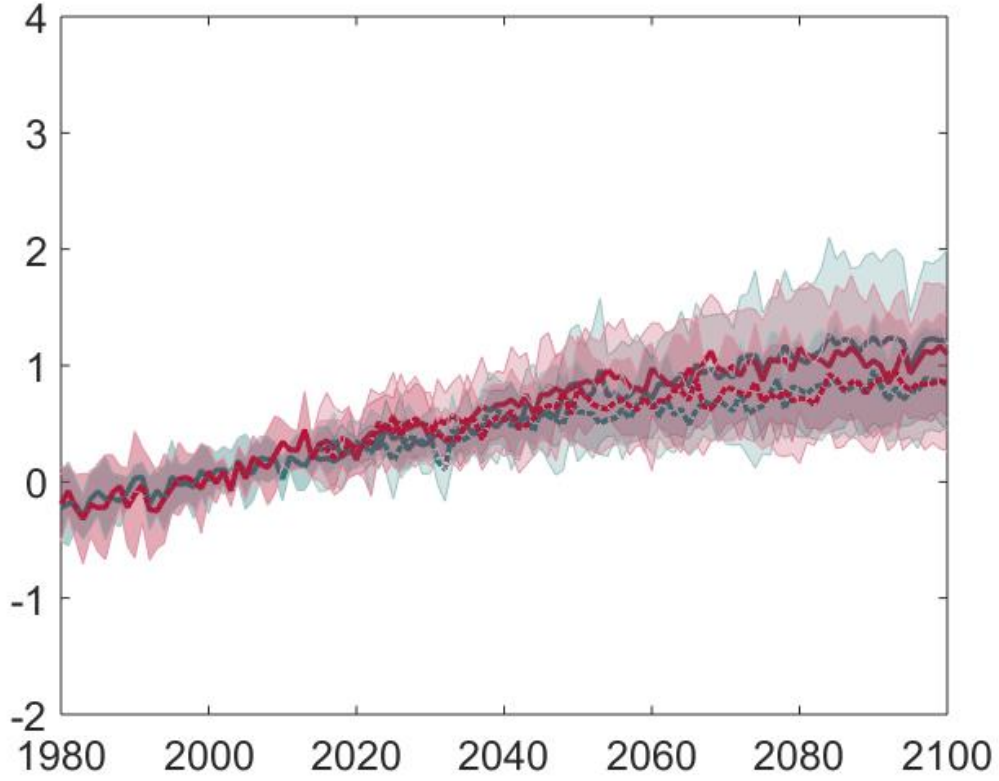
Solid: SSP585
Dotted: SSP245


α
$\alpha_{i\alpha}$
$\alpha_{i\alpha}$
α_c
α_{IRA}
%
%
10
0
-10
-20
-30
3
2
1
-1
-2
-3
1980
1990
2000
2010
2020
2040
2060
2080
2100
Low Regression Models
High Regression Models
ERA5
CERES

Temperature contribution from Estimated $\alpha_{i\alpha}$

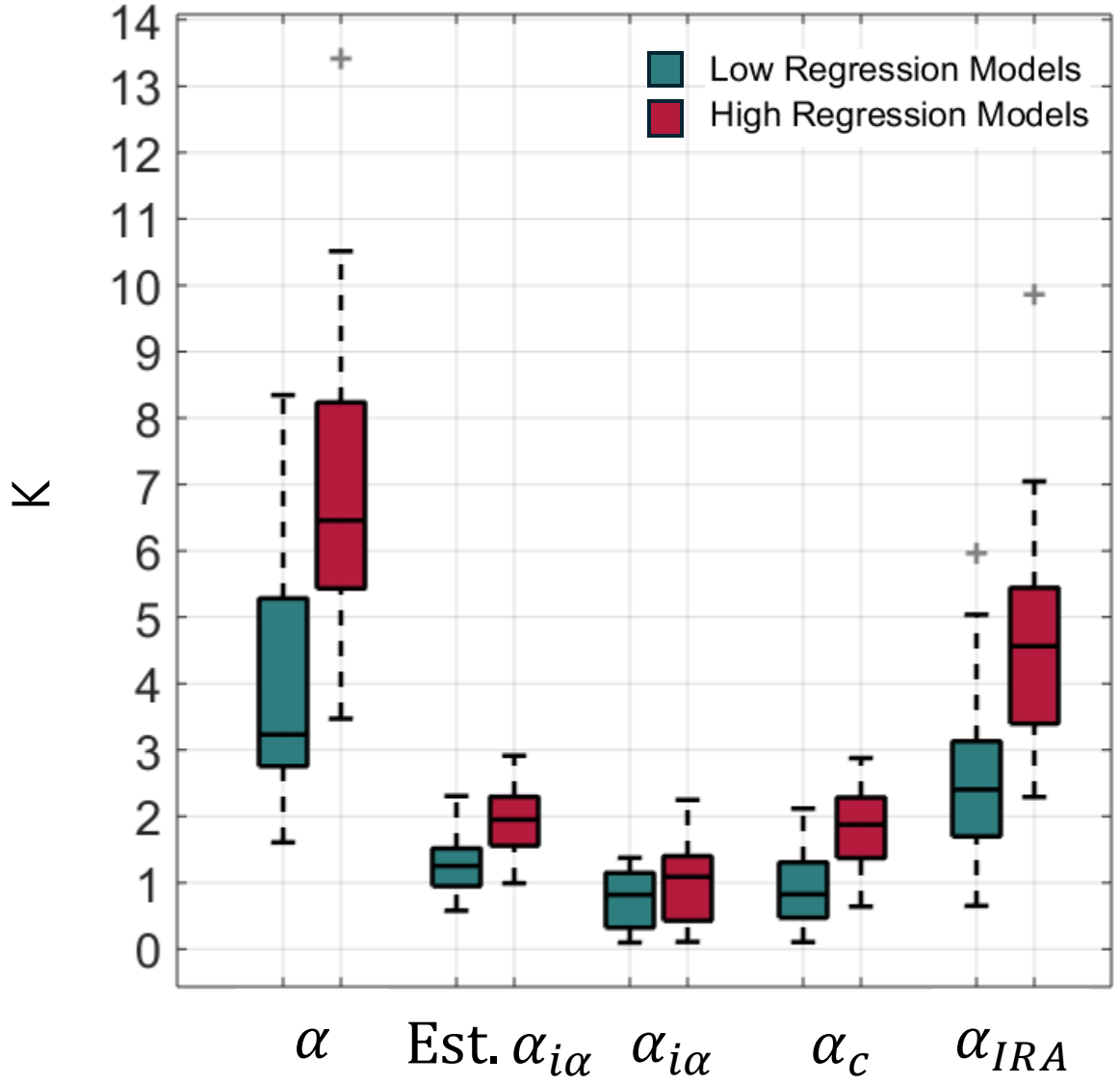


Temperature contribution from $\alpha_{i\alpha}$

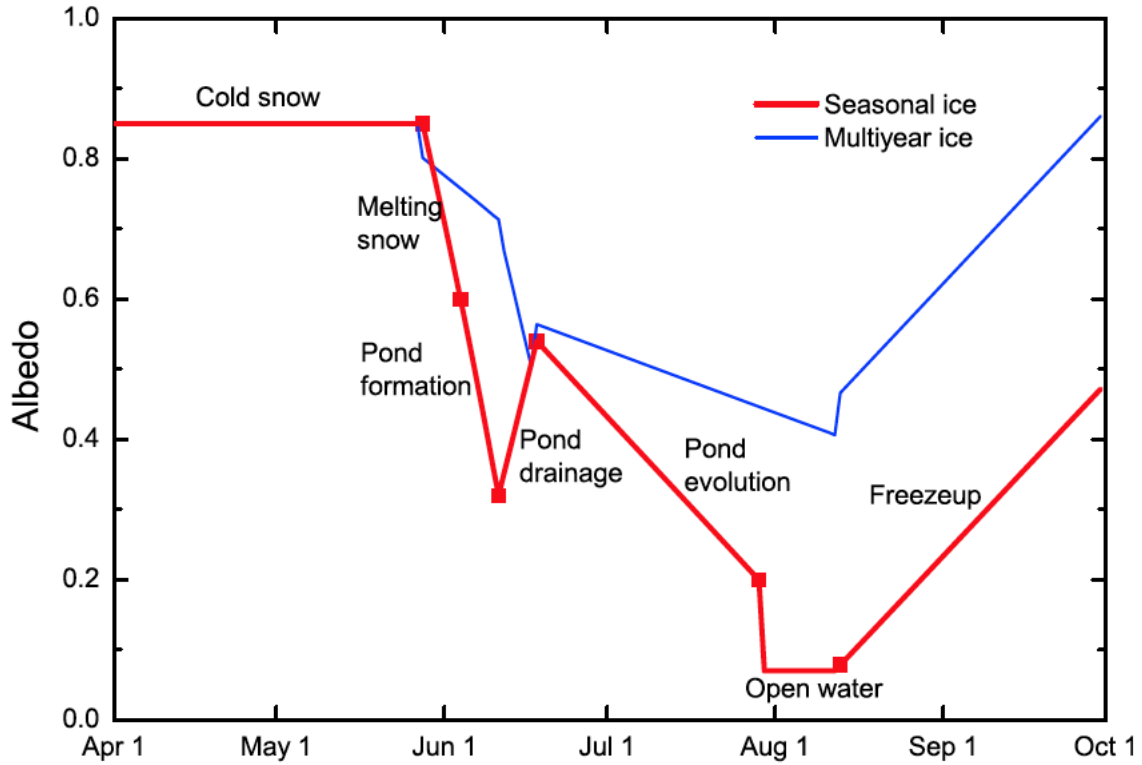


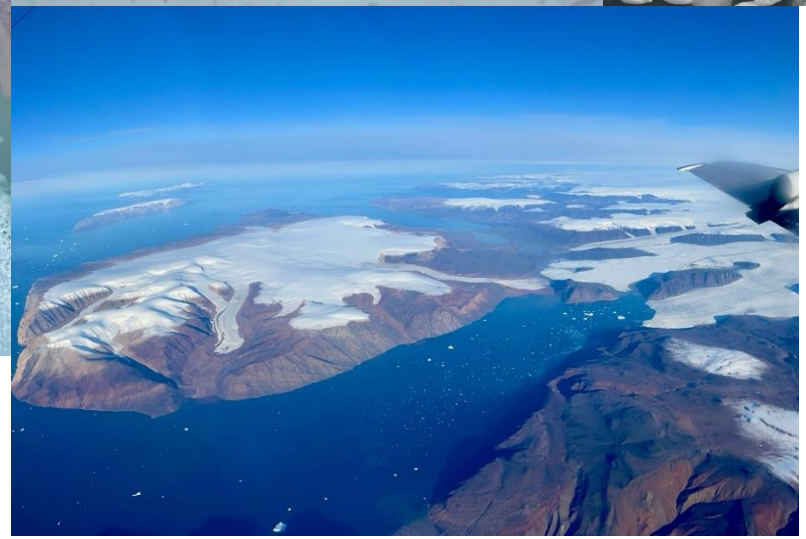
Estimated $\alpha_{ia} = \beta_1 \alpha_c + \beta_2 \alpha_{IRA}$

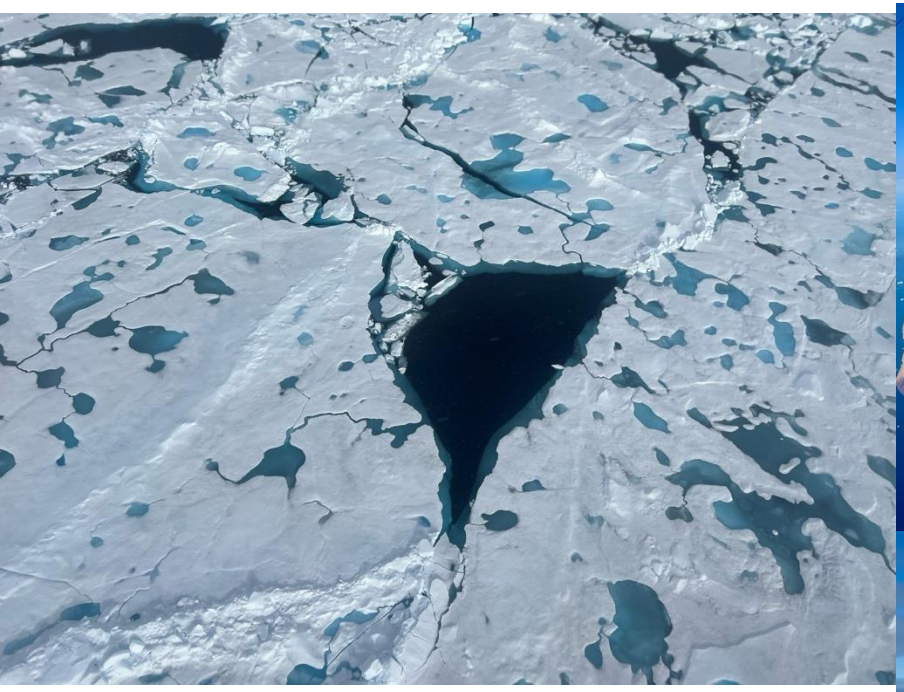
Temperature response (2080-2100)

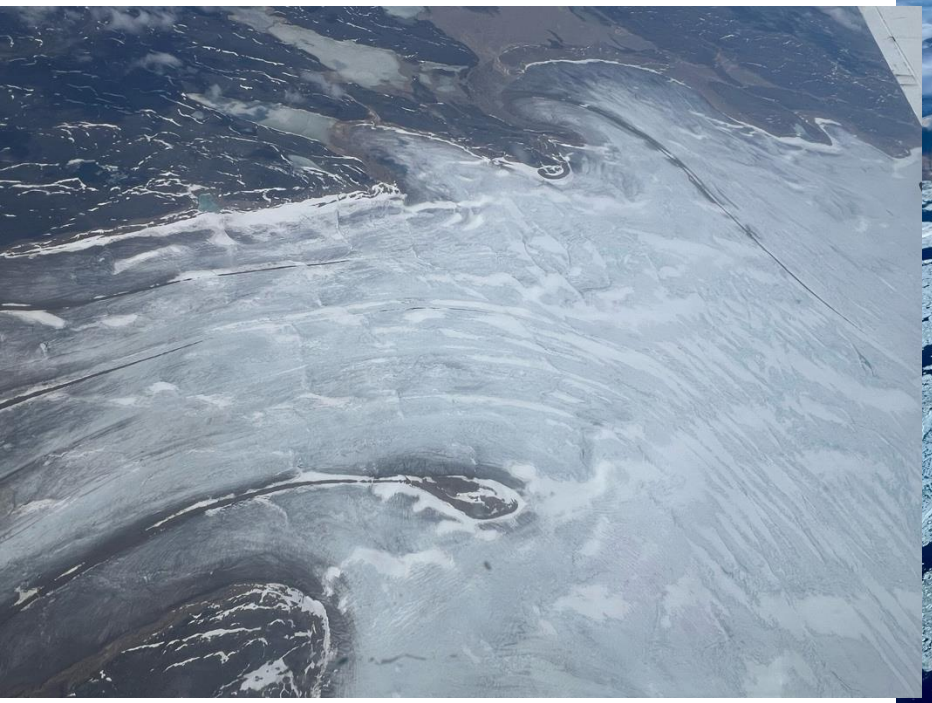


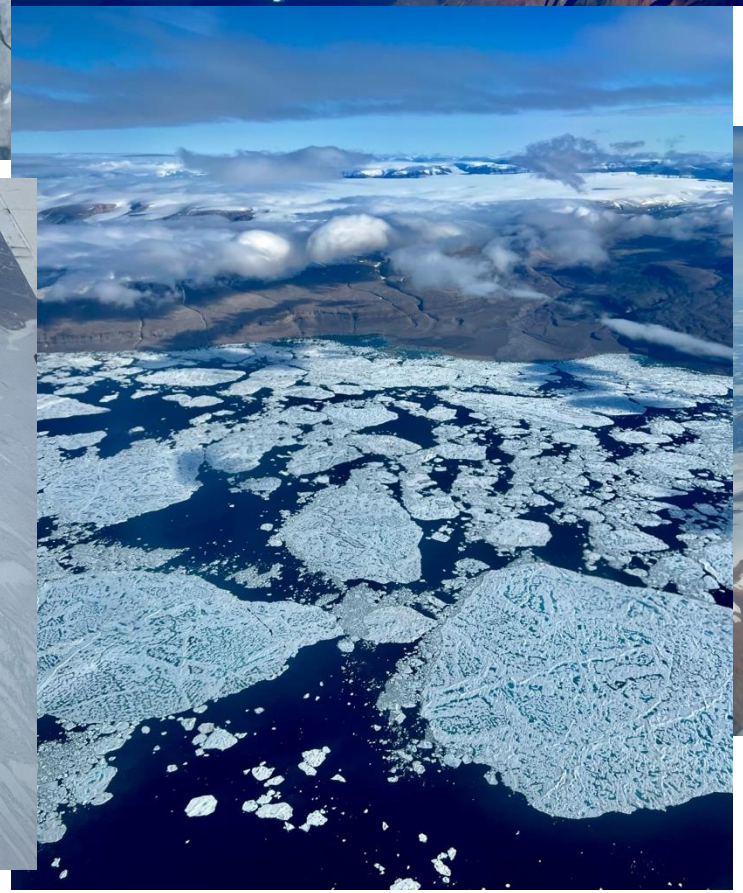
Variations in Arctic surface albedo











Many pictures of Arctic surface albedo