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Estimating Multi-Decadal Cirrus Cloud Top-of-the-Atmosphere Climate Radiative Forcing Trends Across the Warming Arctic

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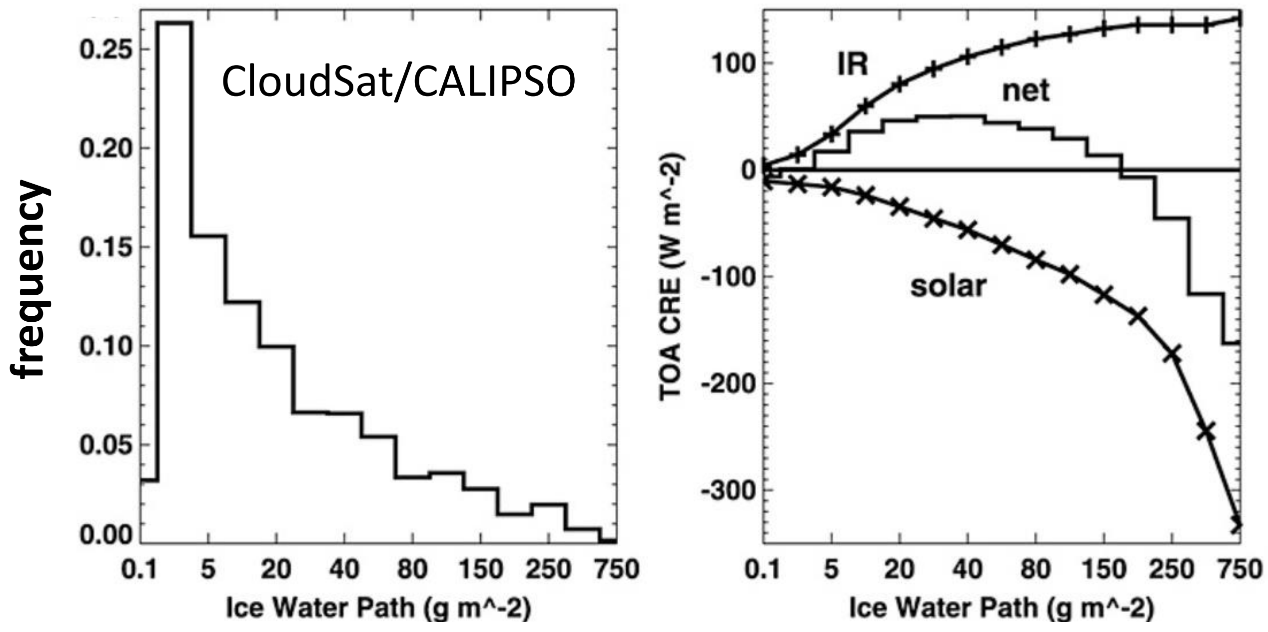
Motivation and Perspective

- Clouds derived from extended satellite lidar/radar records have proven fundamental for diagnosing significant changes to the planetary radiative budget
  - Cirrus clouds are the most common cloud type (global occurrence rate of ~40%)
  - Net cloud radiative forcing (CRF; the difference in clear-sky vs. cloudy radiation budget) magnitude and sign change as a function of IWP (or optical depth)
  - Cirrus are the only cloud type to induce +/- TOA forcing during ***daytime***
- The Polar regions are particularly sensitive to climate change, due to the combination of rapid sea ice (i.e., surface albedo) decline and overall warming

Tropical TTL cirrus (Berry and Mace 2014)



In this study, we seek to estimate changes to top-of-the-atmosphere (TOA) energy balance in the Arctic induced by cirrus clouds over the last forty years

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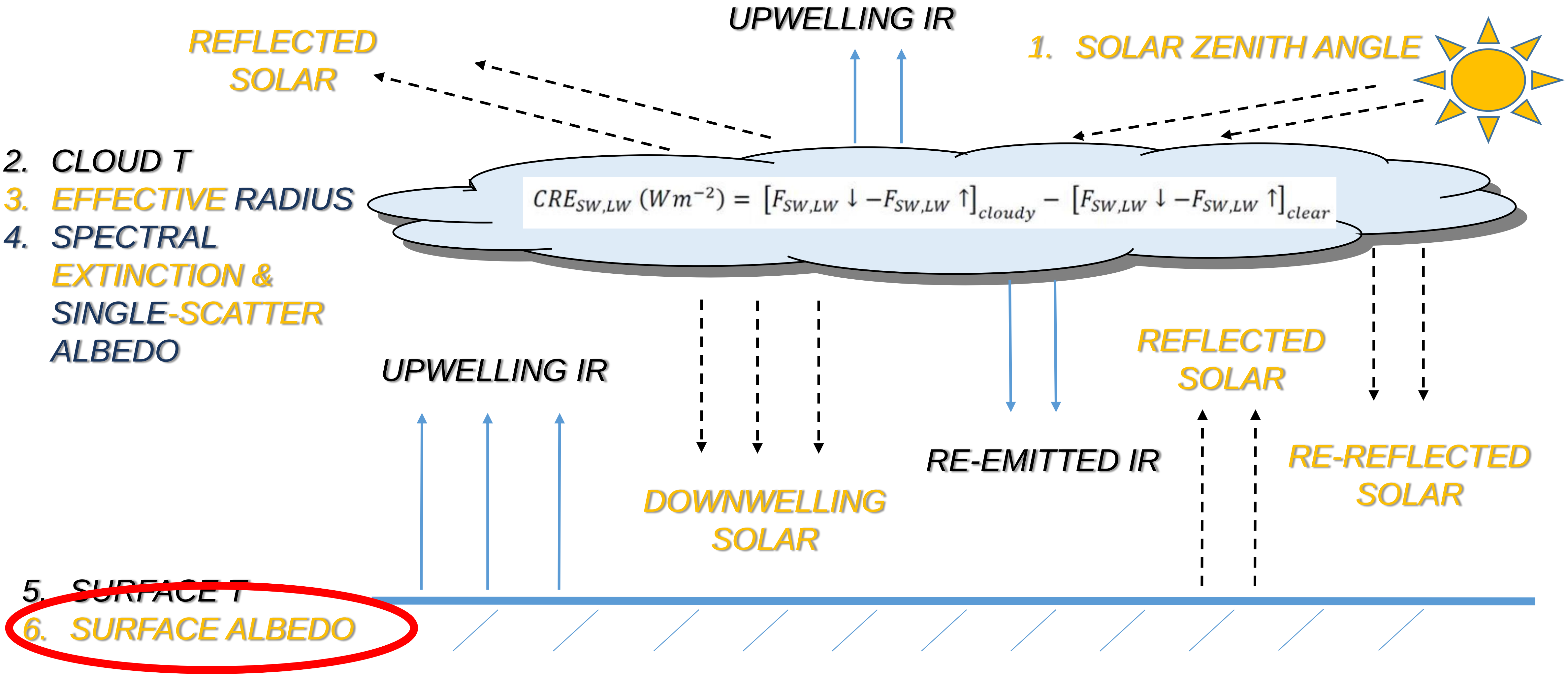
What Influences the Daytime Cirrus Cloud Radiative Forcing?



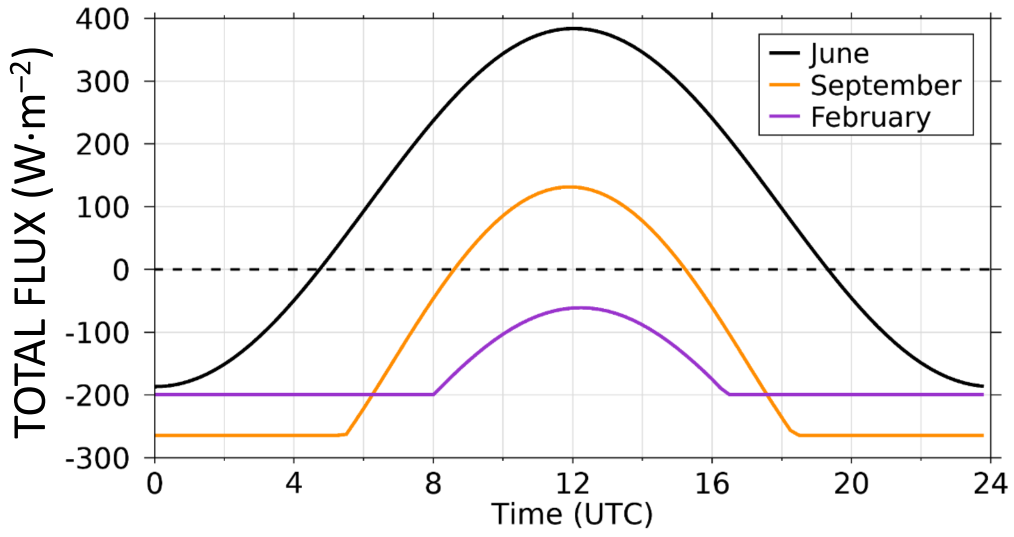
No other region is experiencing as drastic a change in surface albedo as the Arctic and its declining summer sea ice

Experiment Setup & Definitions

More details at Poster 12

Radiative Transfer Model	Meteorology & Surface Albedo	Cloud Heights	Temporal Frequency	COD	Ice Crystal Effective Size	Optical Model
Fu-Liou-Gu; broadband, 1-D	MERRA-2 (0.5° × 0.625°)	CALIOP monthly average; 15-year climo (5° × 5°)*	Once per month**; 5-yr increments	0.03 – 3.0 (22 values)	Dolinar et al. (2022)	8-element column aggregates***

*cirrus definition = transparent (index 7 and 8); cloud optical depth (COD) < 3.0 and cloud top temperature < –37 °C
<u>CALIOP Collection</u>: CAL_LID_L2_05kmCPro-Standard-V4-20
**select the 15th day of each month; use solar geometry consistent with daytime average CRF
***severely roughened ice crystal model (Yang et al. 2013; Bi and Yang 2014; 2017)

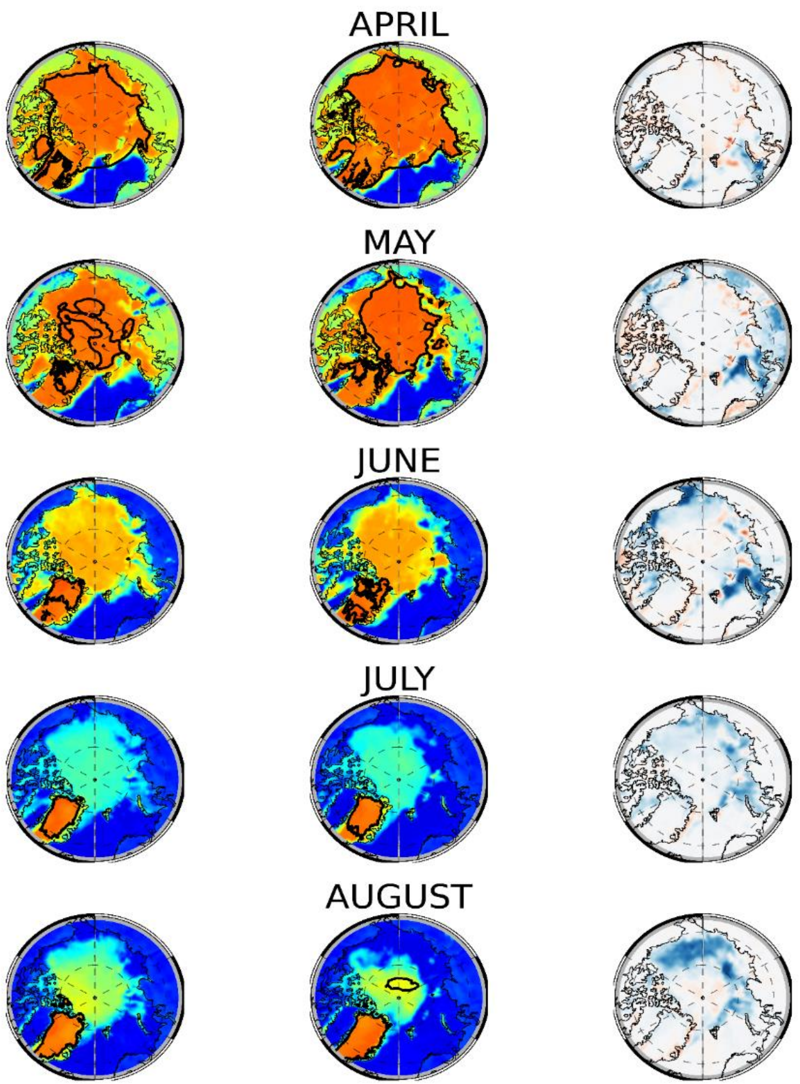


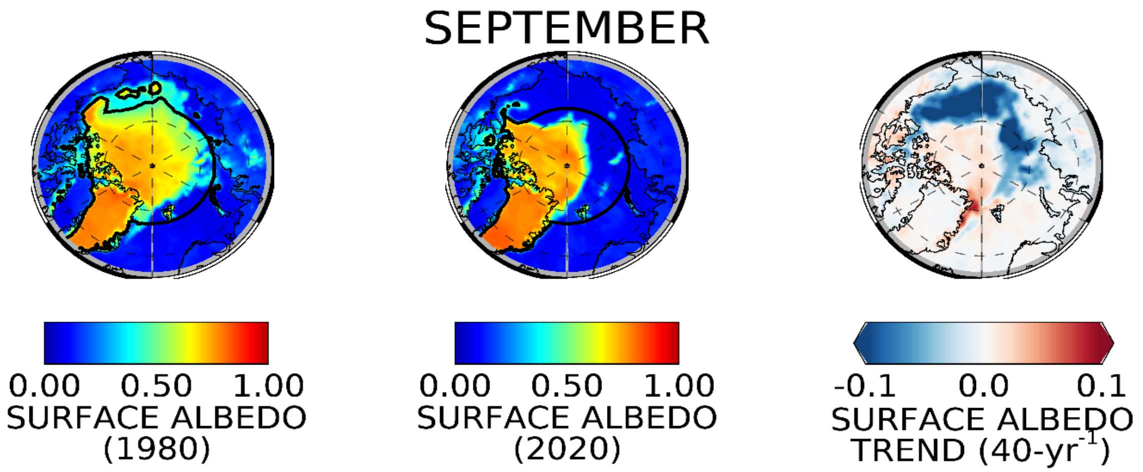
Daytime Definition

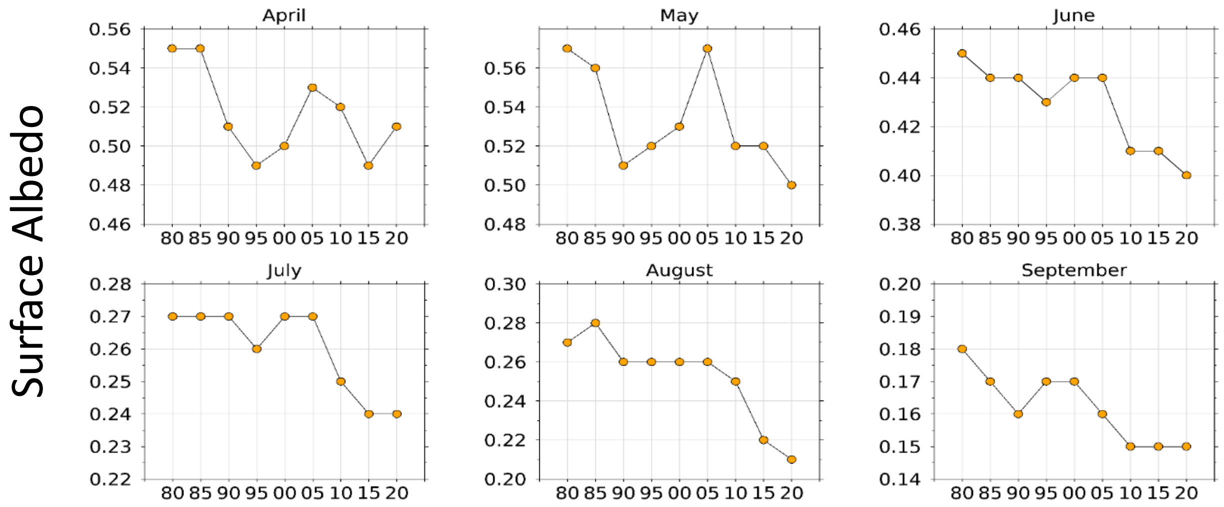
- Time of day when the CRF can be +/-
- Total Flux (@ TOA) = incoming solar – outgoing (solar + IR)
  - Offline calculation: Clear-sky flux computed from climatology (e.g., temperature, water vapor)
  - Daytime = total flux > 0
  - Daytime fraction @ Latitude 71.5 °N (left image)
    - June – 0.61 ; September – 0.28; February – 0.00

Changes in Arctic Surface Albedo (1980 – 2020)

1980 **2020** **Trend**







Nighttime area contained within black contour

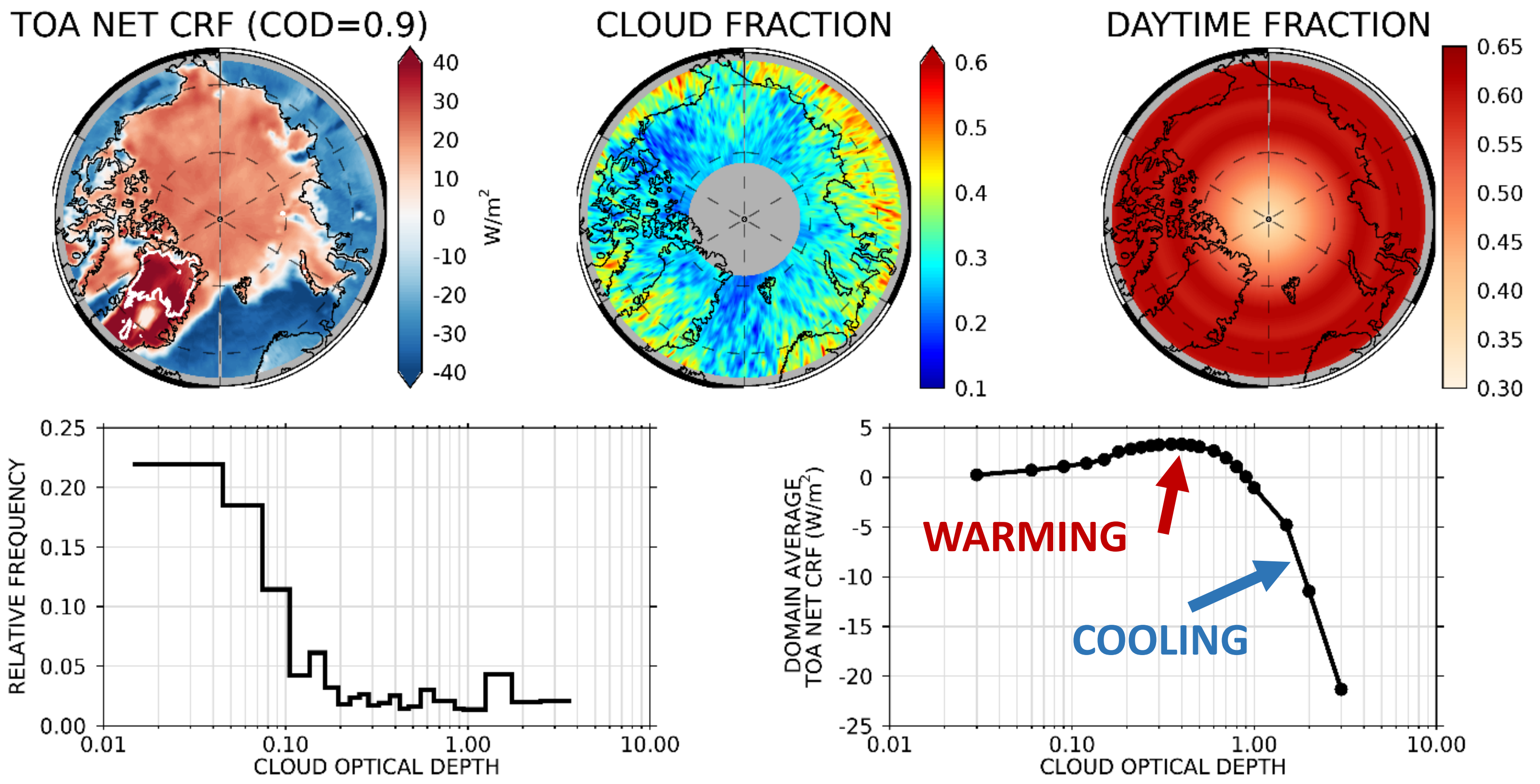
Domain average (bottom)

- Arctic sea ice loss drives the overall decrease in surface albedo
- Some regions have become 10% darker since 1980
- Some regions show an *increase* in albedo

Solving Absolute Daytime TOA Net CRF

Absolute TOA net CRF ($W{\cdot}m^{-2}$) =

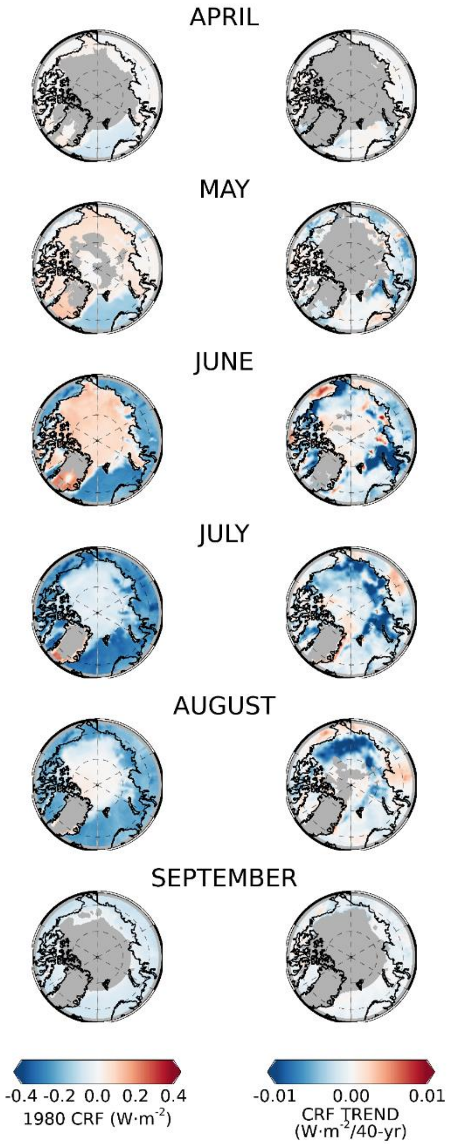
$$CRF(lat, lon, COD, month, year) \times CF(month) \times DF(lat, lon, month) \times RF(COD, month) \times DAF(month)$$



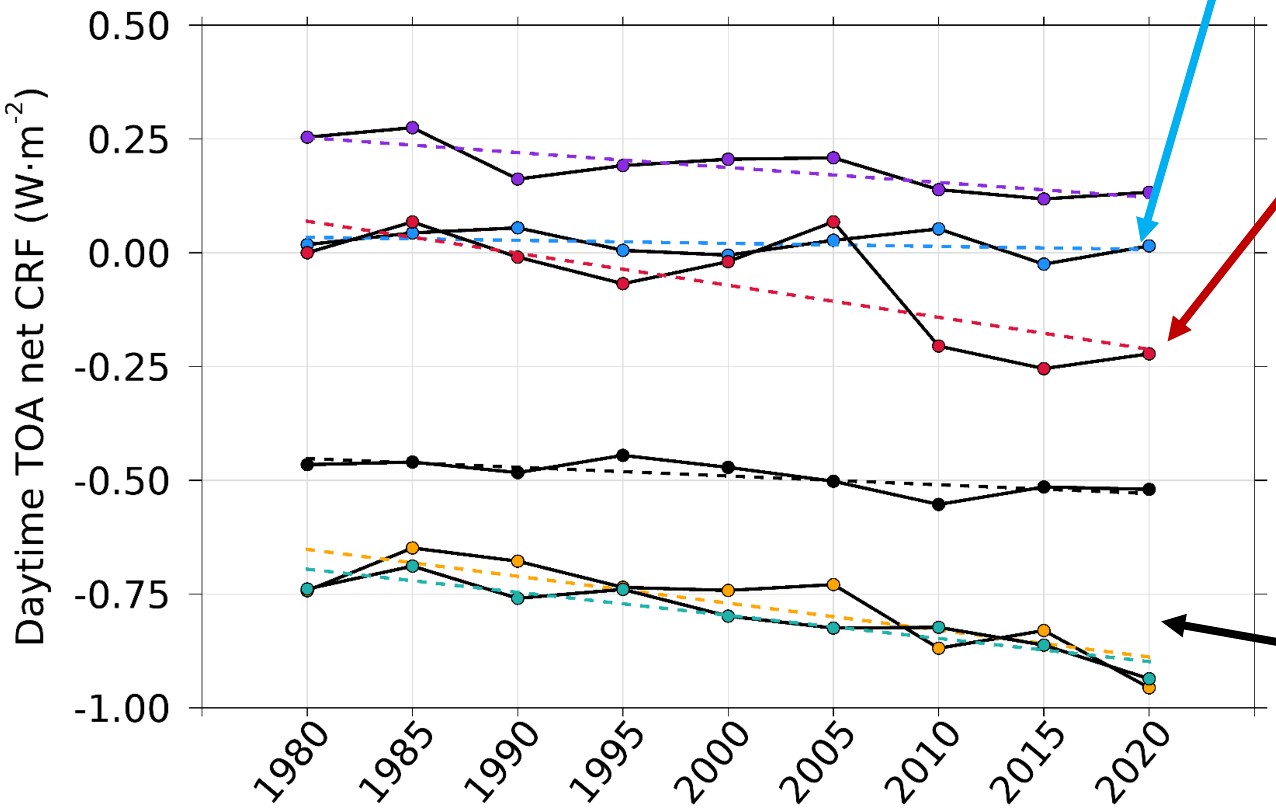
June 1980

- TOA Net CRF (COD = 0.9)
  - Daytime area fraction (DAF) outside of white contour
- Cloud Fraction (CF) – CALIOP (15-year mean)
- Daytime Fraction (DF)
- COD relative frequency (RF) distribution
- TOA Net CRF as a function of COD
  - Each point represents the domain-average TOA net CRF at a given COD

40-Years of Arctic Cirrus Daytime TOA Net CRF



Left column – 1980 estimate
Right column – trend ($W \cdot m^{-2}$ /40-yr)
Grey shade – 2020 nighttime area



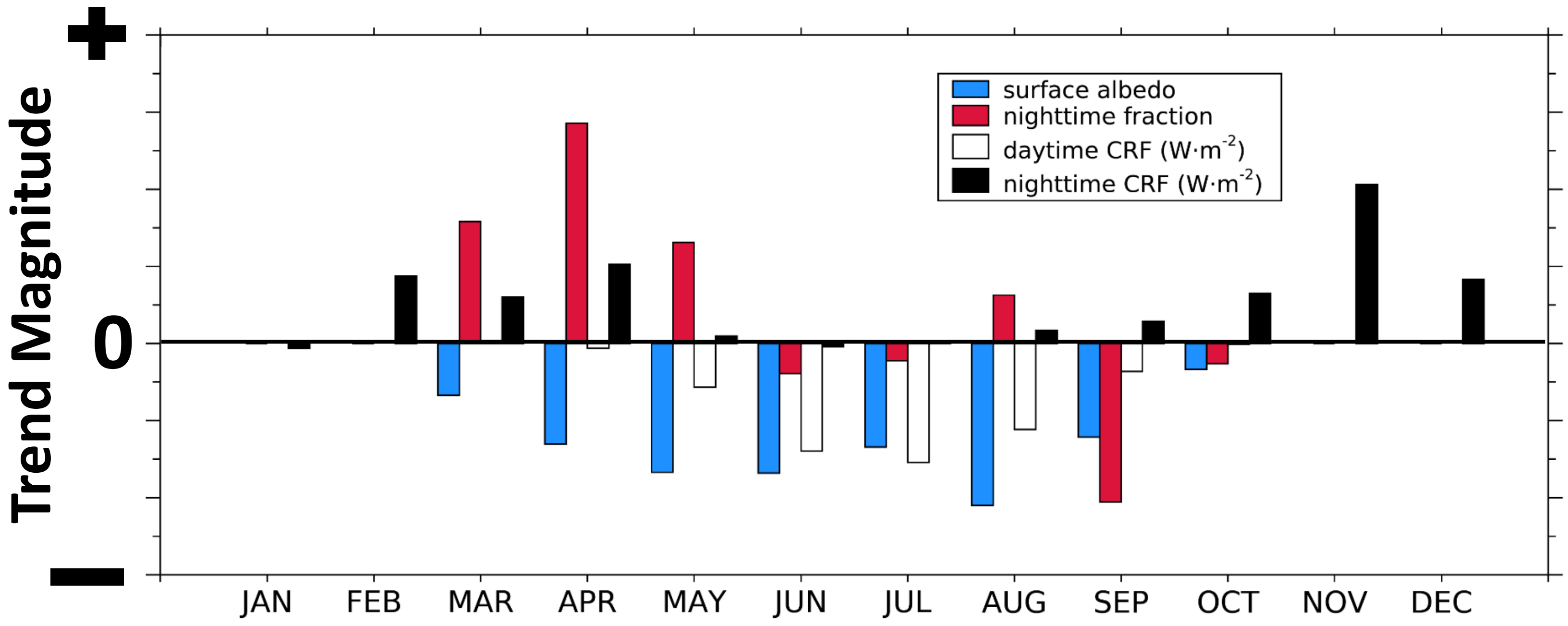
April CRF is relatively stable and near 0 W/m^2

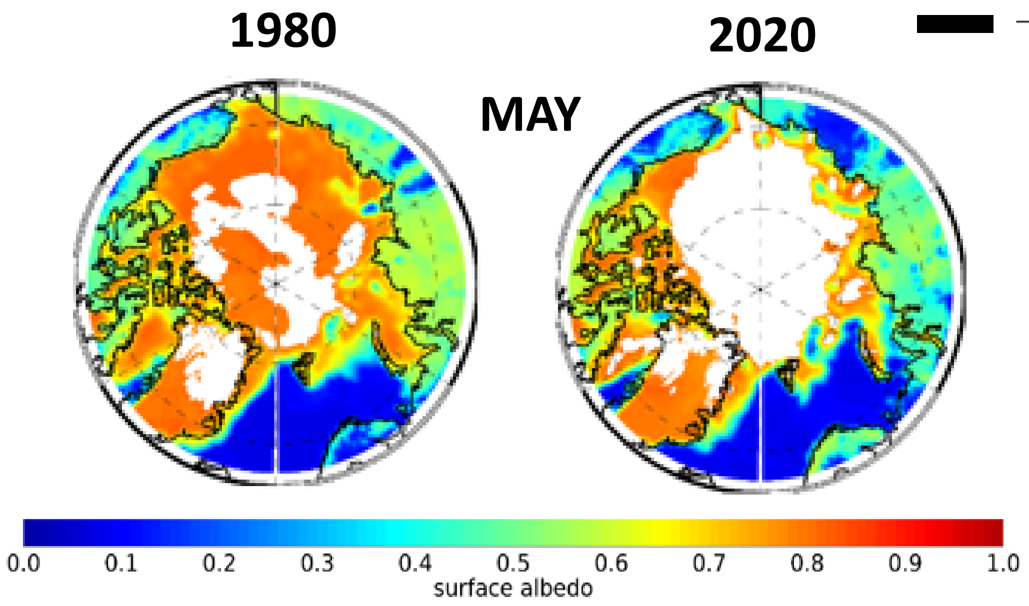
June CRF switches sign and its trend is strongest among all months

Enhanced cooling in **July** and **August** as sea-ice minimums grow more extreme

Notable Trends in Arctic Cirrus Radiative Properties

Parameter	Trend
Albedo	—
Nighttime Fraction	+ —
Daytime CRF	—
Nighttime CRF	+





- **Nighttime fraction** has been increasing since 1980 during months prior to melt onset, indicating an enhancement of nighttime cirrus warming
- Decrease in nighttime fraction during months of sea ice melt coincides with enhancement in daytime cooling

Summary

- The Arctic has warmed at an alarming pace over the last forty years. However, cirrus clouds are acting to increasingly cool the region during daylit hours, driven by sea-ice reduction and suppressing of the albedo-driven warming.
- We've also discovered that 'Radiative Polar Night' conditions are actually increasing prior to the melt season due to regional warming. Overall cirrus cooling is still occurring, however, in spite of this decrease in total daylit area.
- Clouds derived from extended satellite lidar/radar records have proven fundamental for diagnosing significant changes to the planetary radiative budget. EarthCARE is critical to continuing the polar cloud record for extended climate study.
- Our goal is to replace climatological cloud with a twenty-year CALIOP/EarthCARE cloud record by the middle of this decade.