The changing Arctic surface energy budget: The role of clouds

Patrick C. Taylor
Science Directorate
NASA Langley Research Center
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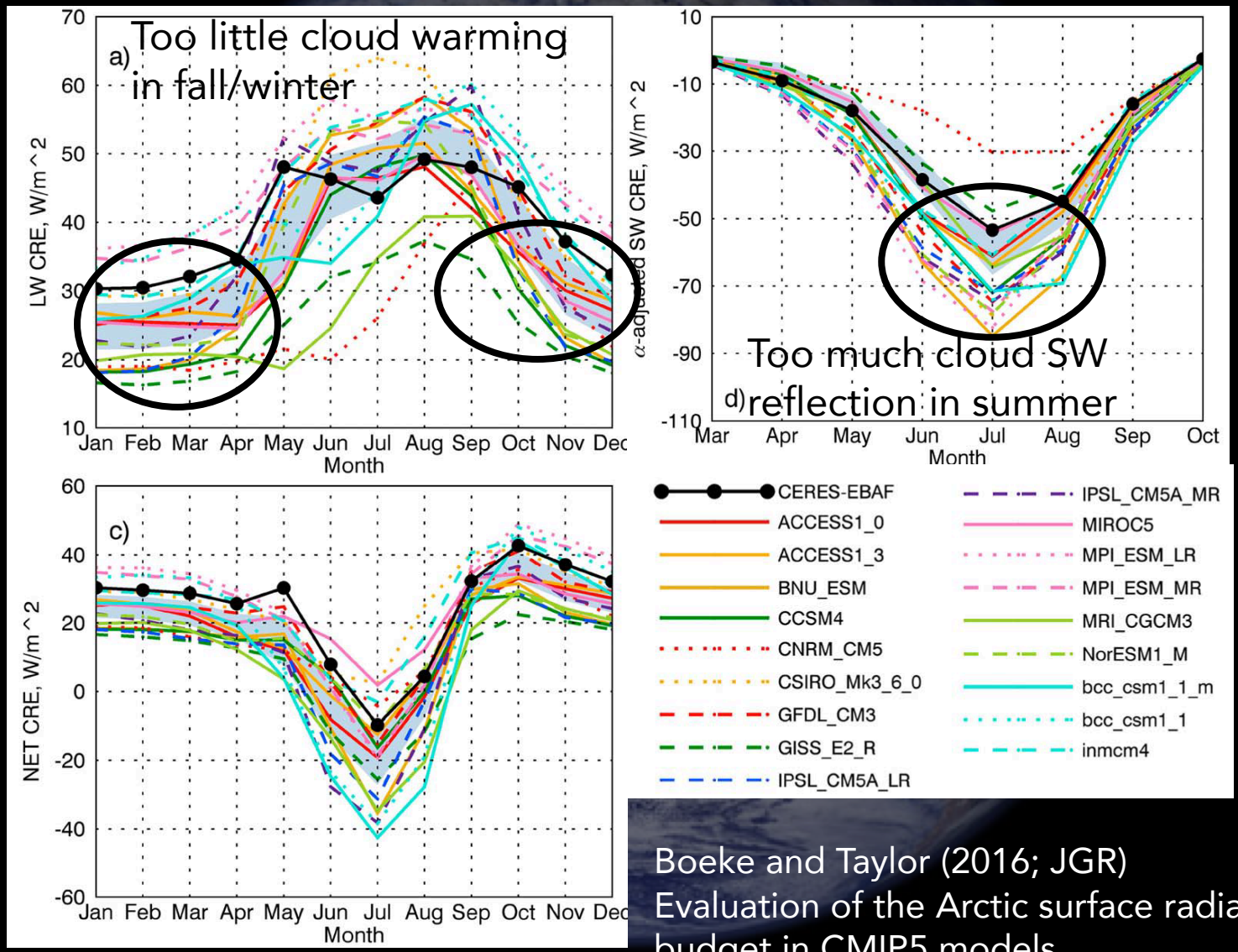
patrick.c.taylor@nasa.gov

Climate models struggle to simulate the surface cloud radiative effect annual cycle

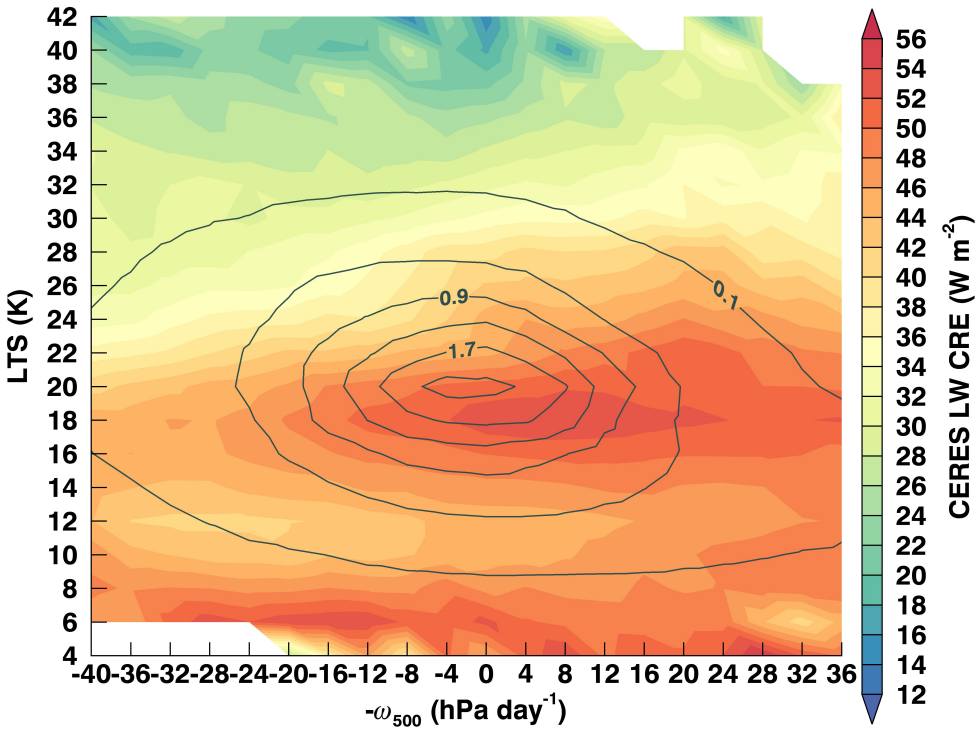


Boeke and Taylor (2016; JGR)
Evaluation of the Arctic surface radiation budget in CMIP5 models

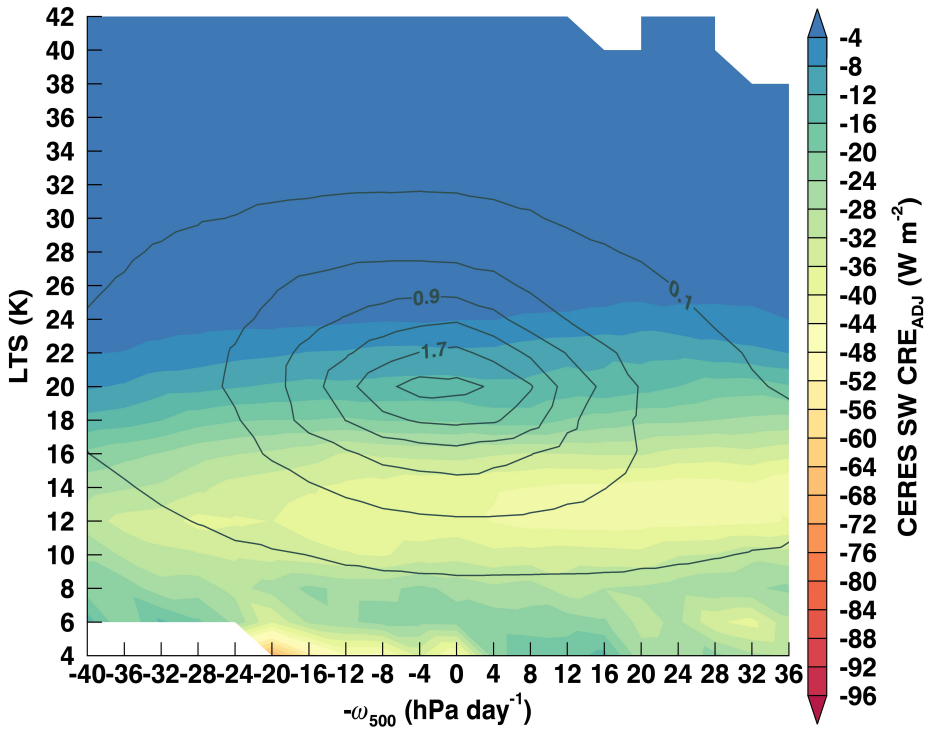
Regime Decomposition: LTS and Omega_500

CERES Annual Mean

LW CRE



SW CRE

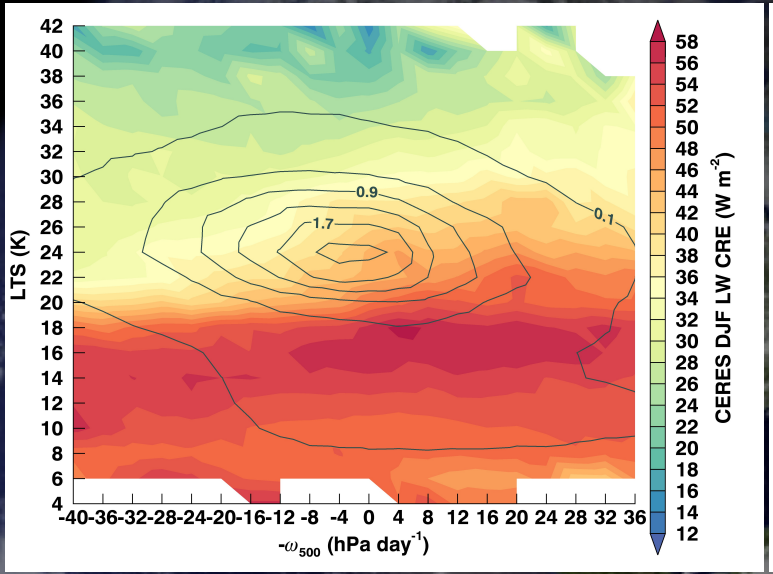


Regime Decomposition: LTS and Omega_500

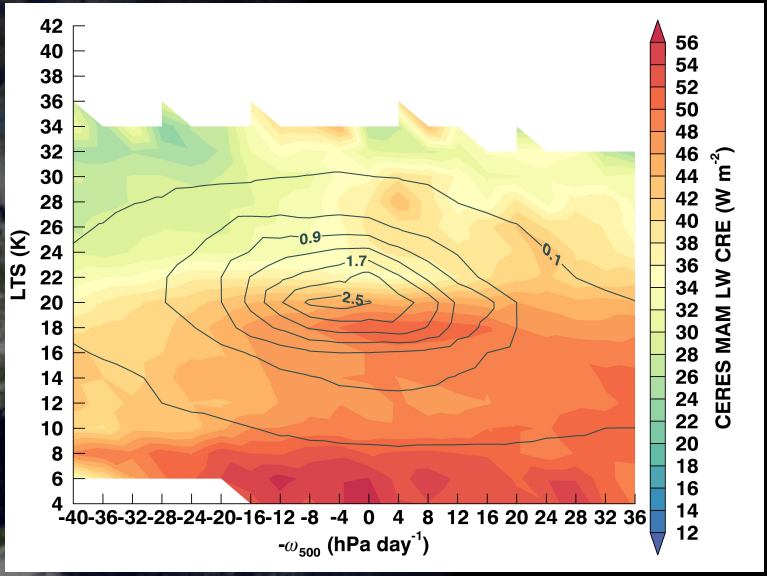
CERES Seasonal LW CRE

Both the CRE within regimes and the frequency of occurrence vary with season.

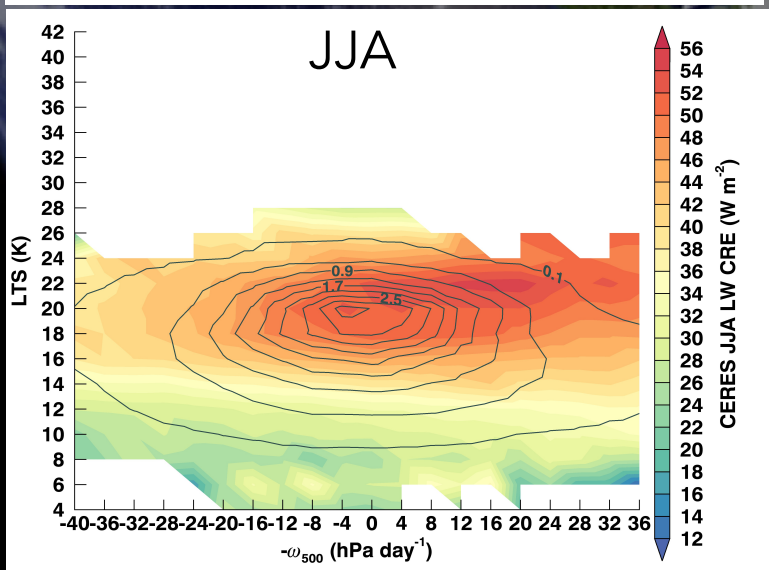
DJF



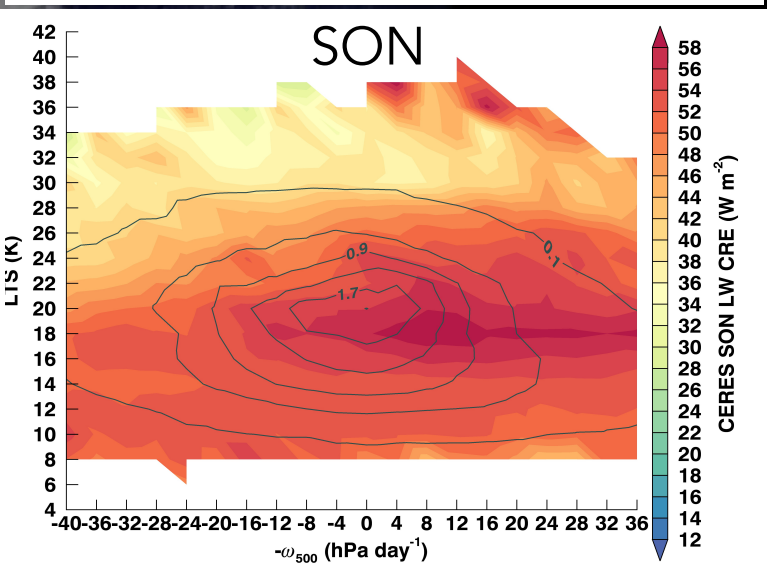
MAM



JJA

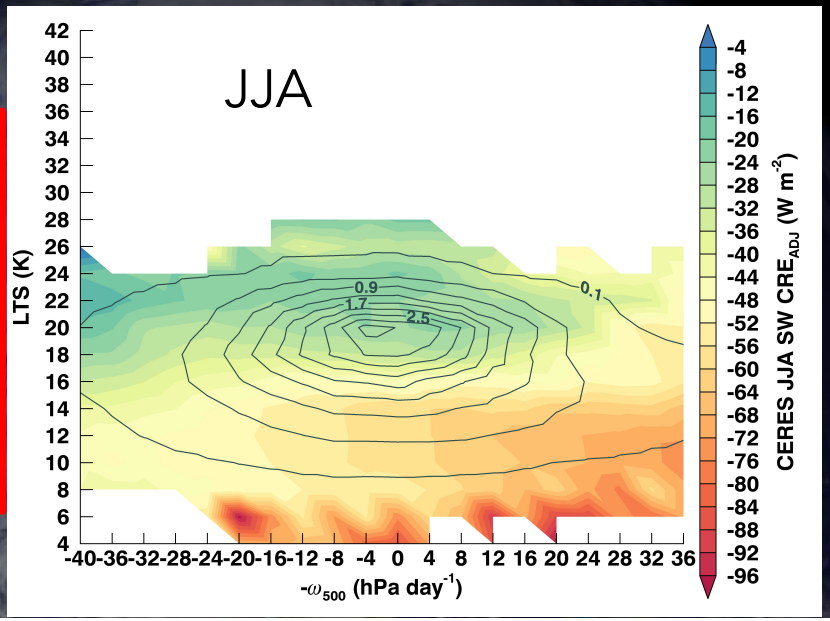


SON

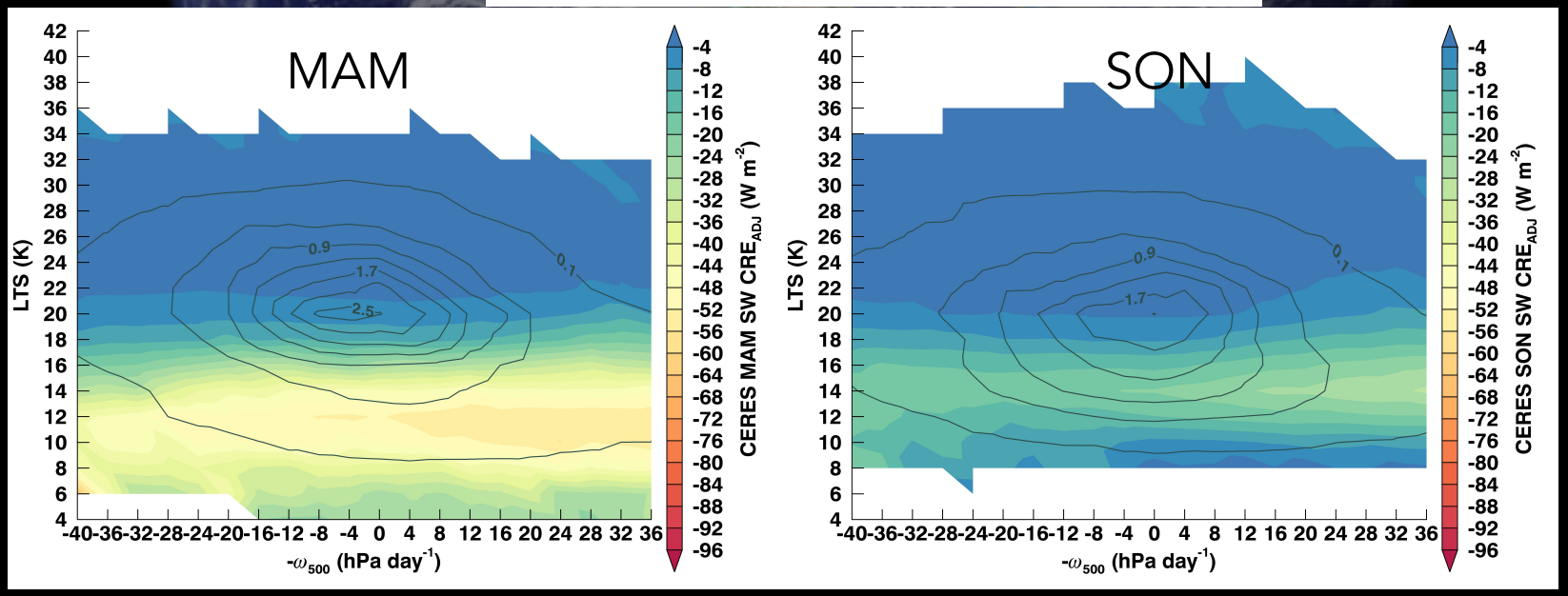


Regime Decomposition: LTS and Omega_500

The same atmospheric regimes contribute to the SW CRE for all seasons.



CERES Seasonal SW CRE



Intergroup LCA differences: Regime frequency of occurrence or LCA joint PDF?

Low Cloud Amount Joint PDF

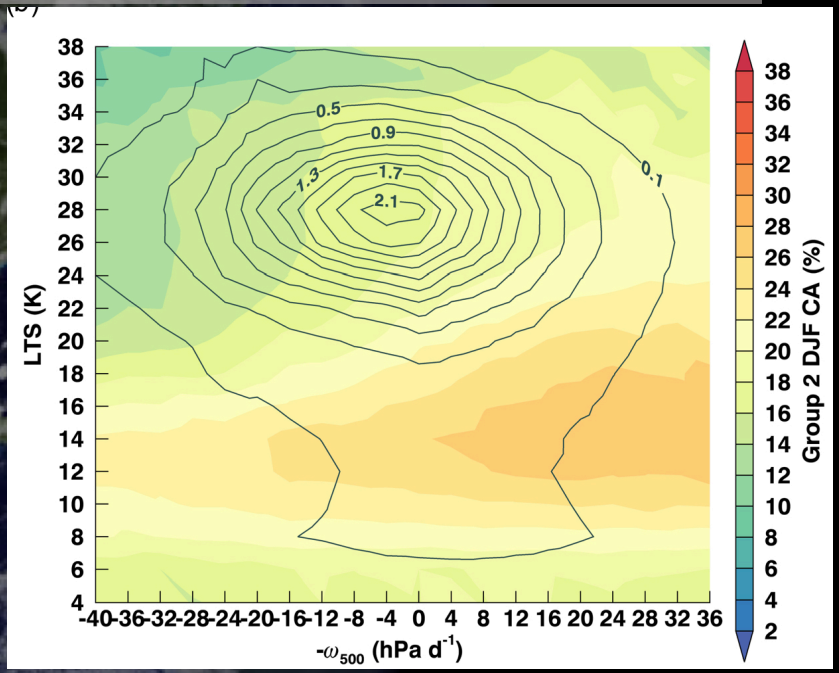
Atmospheric Regime Relative Frequency of Occurrence

$$\overline{LCA} = \sum_{i,j} LCA(LTS_i, -\omega_{500,j}) * RFO(LTS_i, -\omega_{500,j})$$

Group average LCA can be estimated by summing the average LCA within each regime weighted by its RFO.

Agreement within 1.3%	Group 1	Group 2
DJF domain-averaged LCA	29.0 %	17.2 %
DJF LCA from Eq. (1)	29.8 %	16.3 %
JJA domain-averaged LCA	23.1 %	27.0 %
JJA LCA from Eq. (1)	21.8 %	26.1 %

Taylor et al. (2019; ACP)



"Parameterizing" low cloud amount by the mean values within LTS-omega_500 regimes reproduces the mean winter and summer mean values within 1.3%

Intergroup CRE differences: Regime frequency of occurrence or CRE joint PDF?

$$\overline{\delta CRE_{G1-G2}} = \sum_{i,j}\left[\left(\delta CRE\left(LTS_i, -\omega_{500,j}\right)_{G1-G2} * RFO\left(LTS_i, -\omega_{500,j}\right)_{G1}\right)\right] + \sum_{i,j}\left[\left(CRE\left(LTS_i, -\omega_{500,j}\right)_{G1} * \delta RFO\left(LTS_i, -\omega_{500,j}\right)_{G1-G2}\right)\right]$$

Term 1: δCREdue to δCRE(LTS, $-\omega_{500}$)

Term 2: δCRE due to δRFO

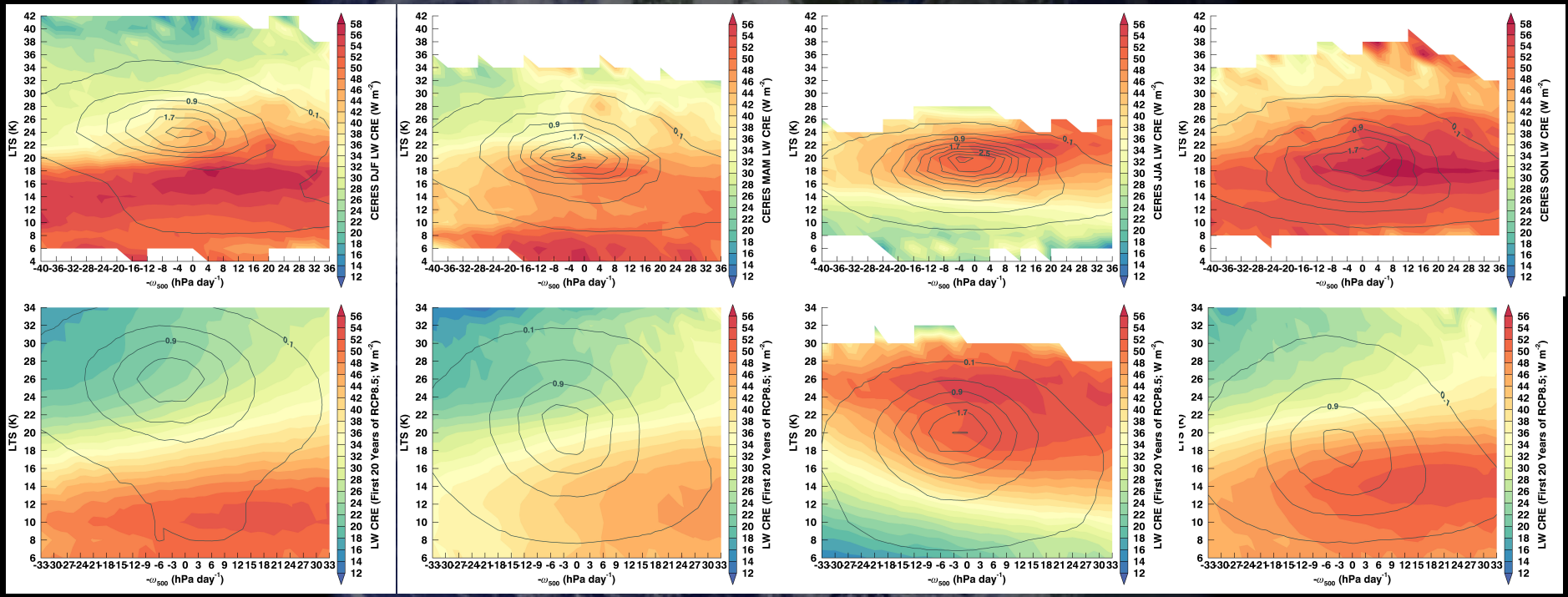
CERES	DJF	MAM	JJA	SON
Domain-avg LWCRE anomaly	-3.47	-3.51	-0.29	7.27
$\delta LWCRE$ from decomposition	-3.94	-3.44	-0.17	7.52
δLW CRE $(LTS_i, -\omega_{500,j})$	1.07	-3.73	-3.24	6.67
δRFO	-5.01	0.29	3.08	0.84

Regime Decomposition: LTS and Omega_500

Seasonal LW CRE

DJF MAM JJA SON

CERES



CMIP5

The CMIP5 model ensemble exhibits substantial seasonal differences with CERES and the frequency of atmospheric states.

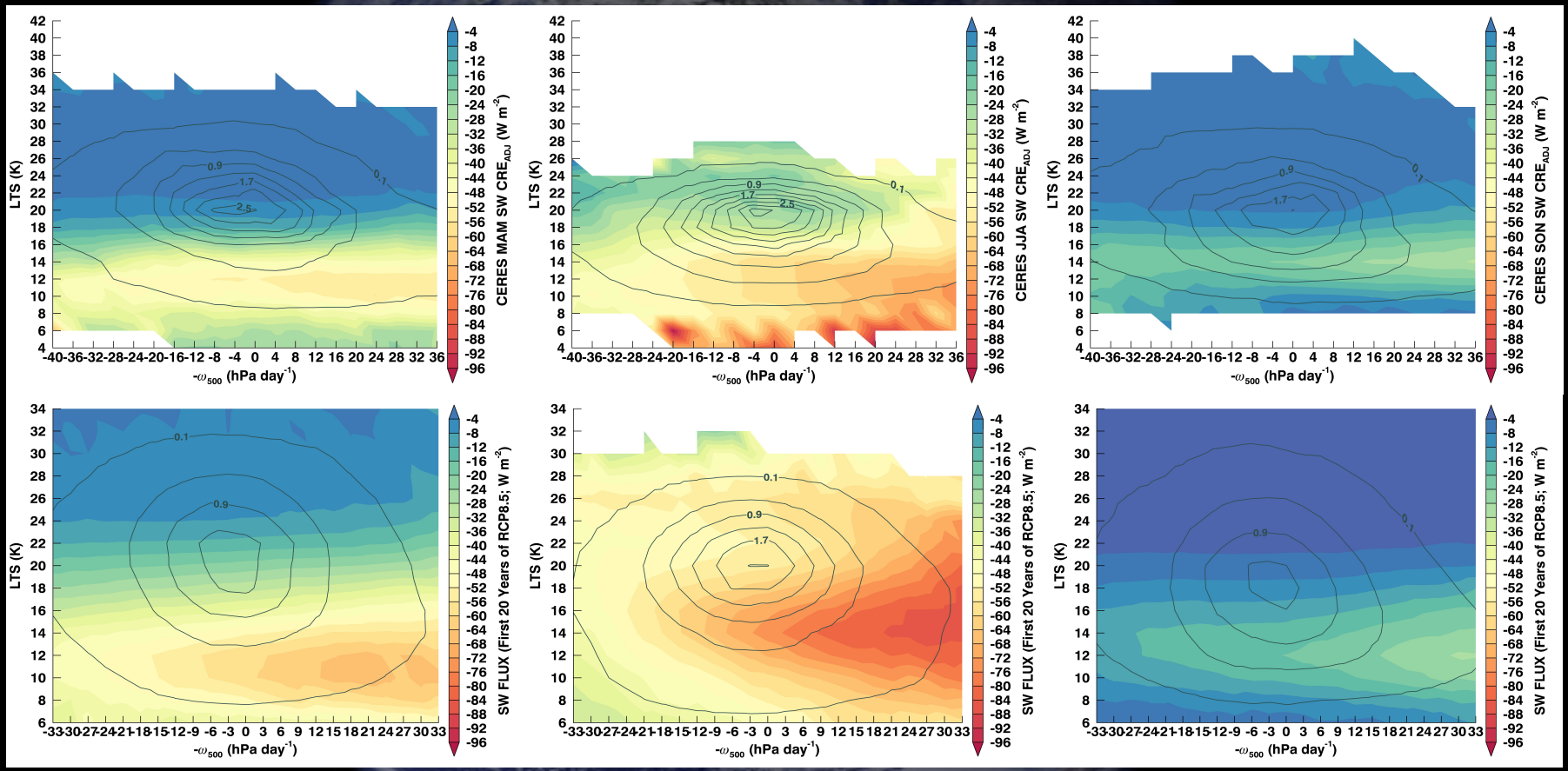
Regime Decomposition: LTS and Omega_500

Seasonal SW CRE

MAM JJA SON

CERES

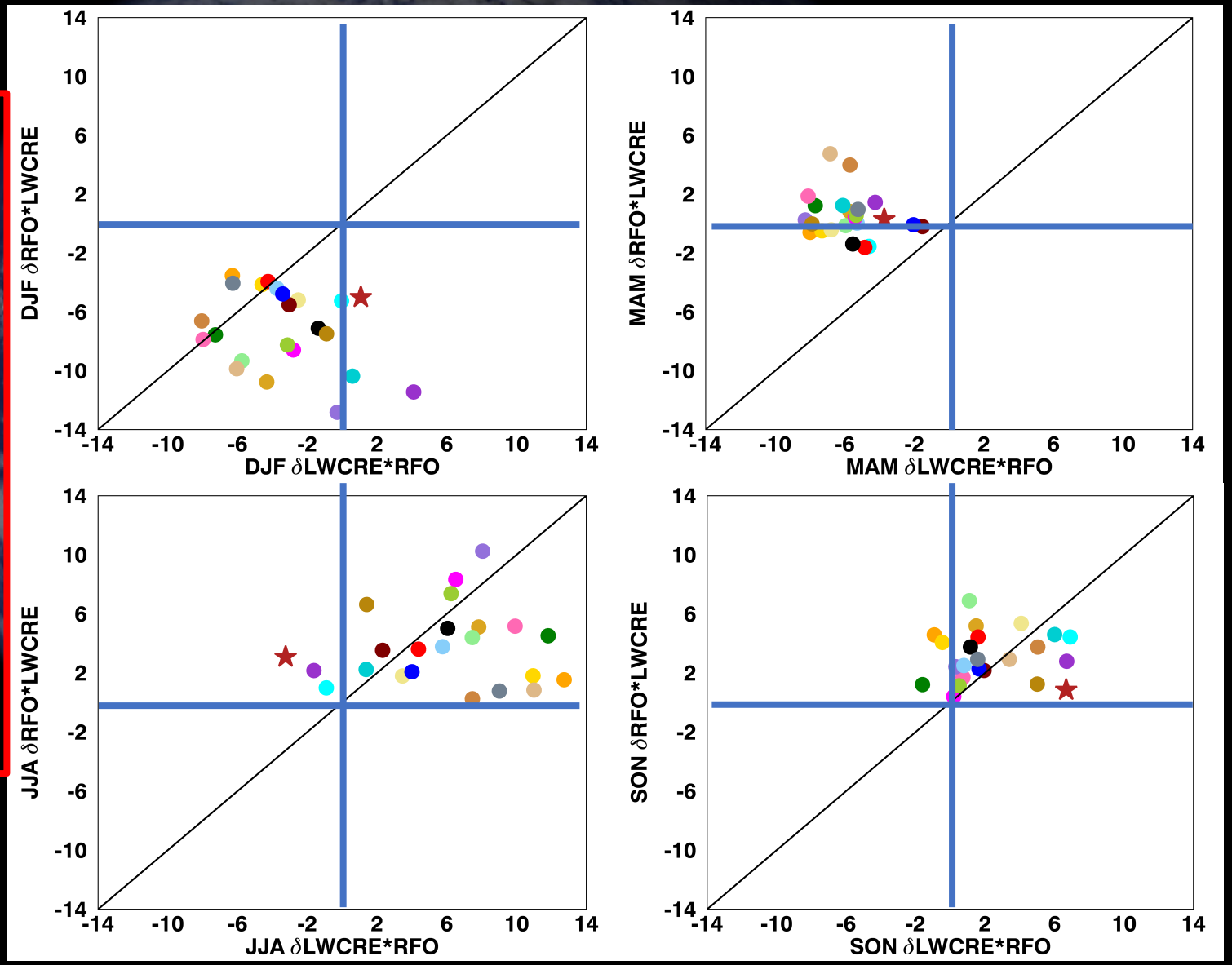
CMIP5



The CMIP5 model ensemble exhibits substantial seasonal differences with CERES and the frequency of atmospheric states.

Frequency of Occurrence vs. regime CRE: LW

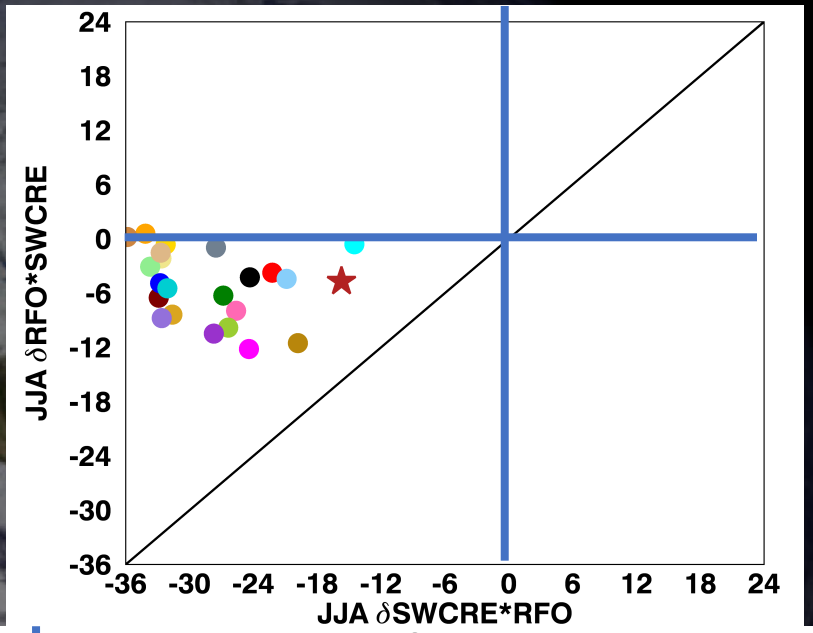
The relationship between LW CRE and atmospheric regime is most important in Spring, Summer, and Fall, whereas changes in the frequency of atmospheric states is most important in winter.

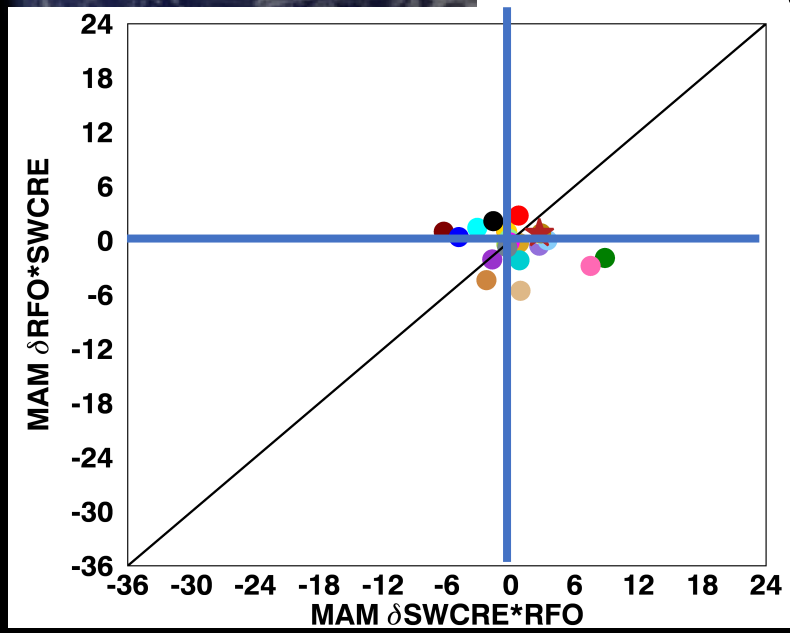


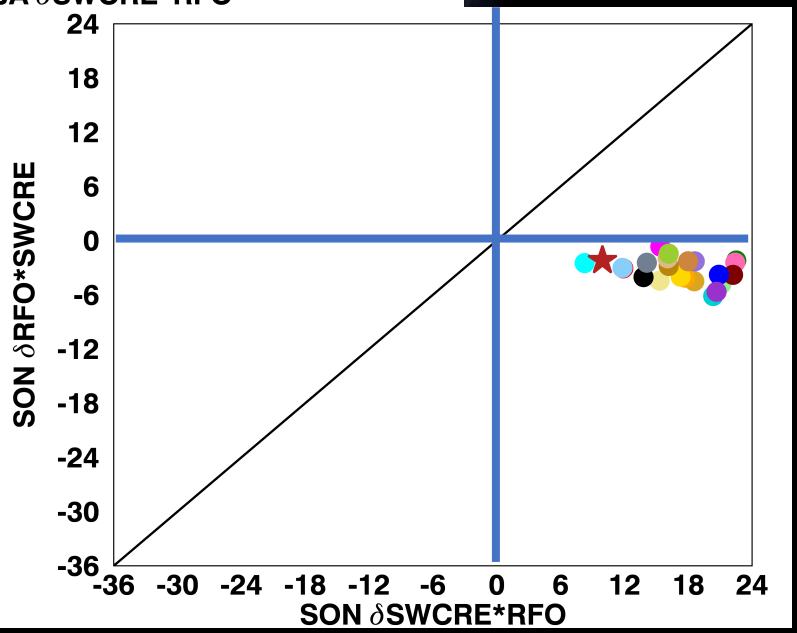
Frequency of Occurrence vs. regime CRE: SW

The relationship between SW CRE and atmospheric regime is most important in Spring, Summer, and Fall.

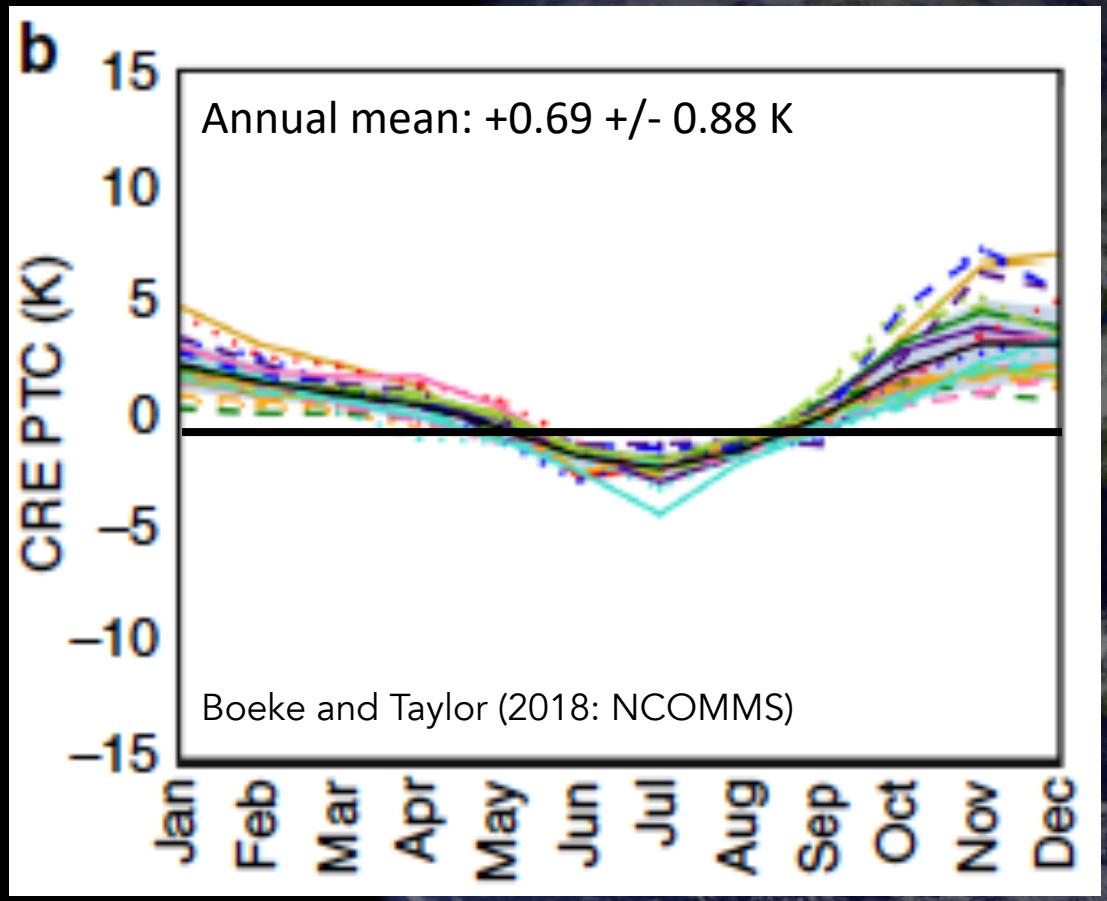
CMIP5 models exhibit much larger differences between the SW CRE by atmospheric regime than shown using CERES, especially in summer.







Cloud contributions to Arctic surface warming

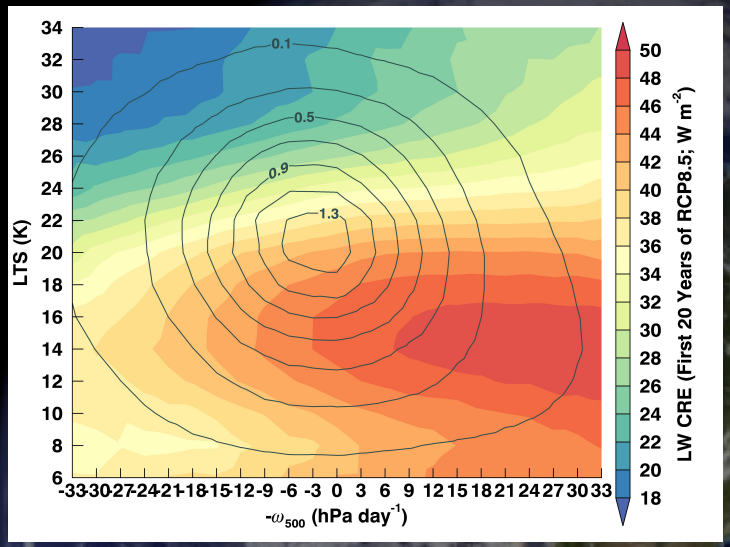


- Arctic cloud feedbacks cool the surface in summer and warm the surface in fall and winter.
- Annual mean cloud feedback is a warming.
- The largest inter-model spread is found in fall.

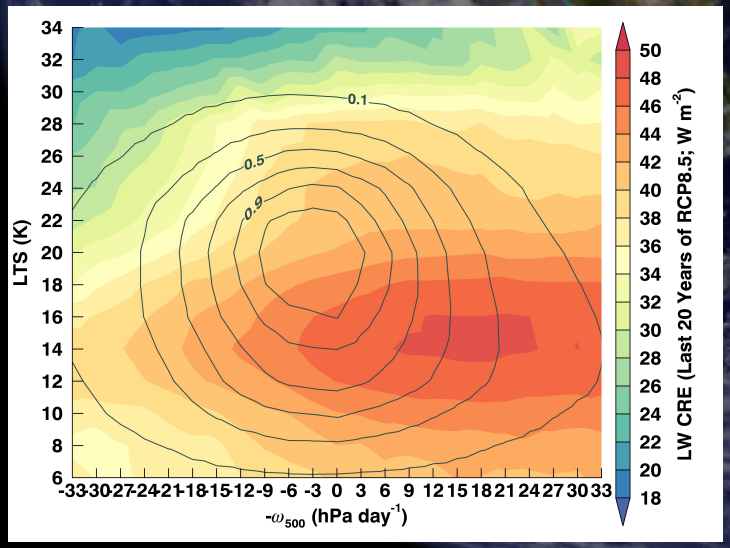
Seasonal structure of the cloud contribution to the seasonal Arctic warming pattern is robust across CMIP5 models.

Annual mean change in LW CRE:

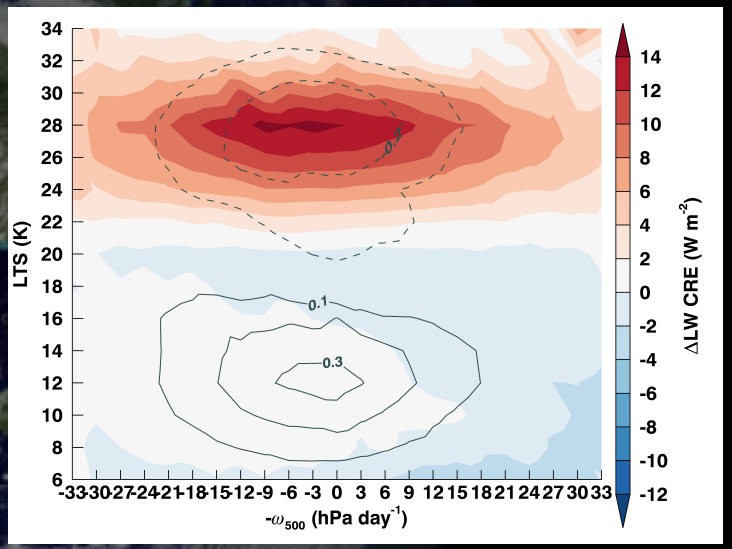
First 20 Years of RCP8.5



Last 20 Years of RCP8.5



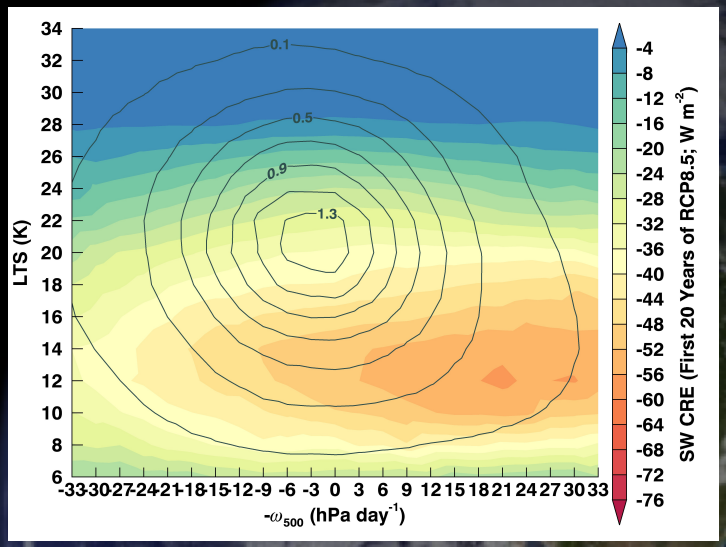
Difference (Last 20 – First 20 years)



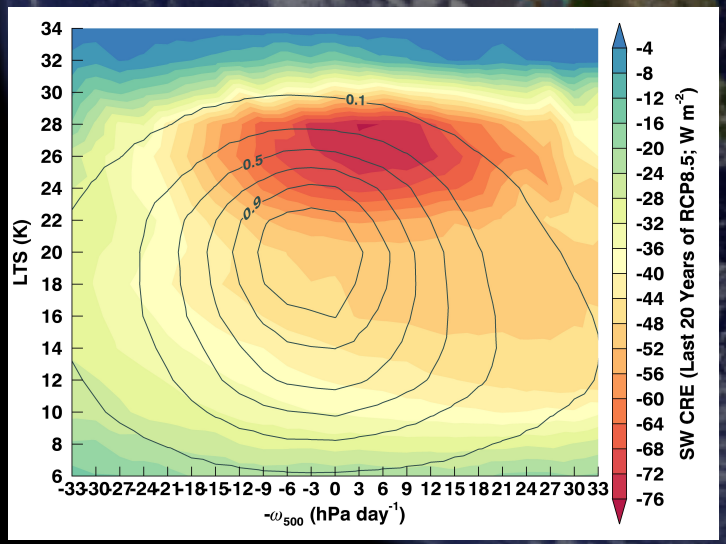
LW CRE change is positive in the higher LTS conditions

Annual mean change in SW CRE:

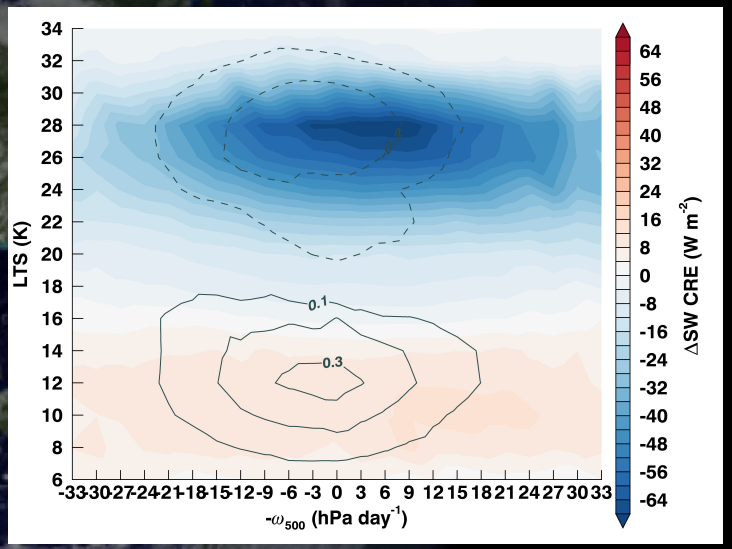
First 20 Years of RCP8.5



Last 20 Years of RCP8.5



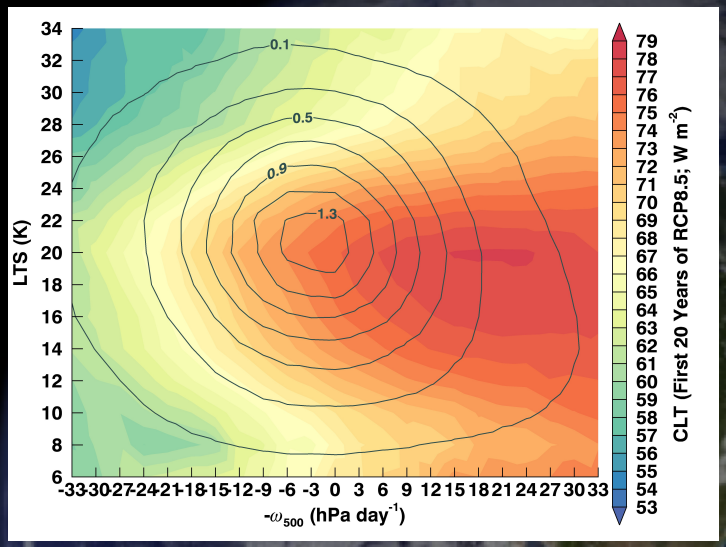
Difference (Last 20 – First 20 years)



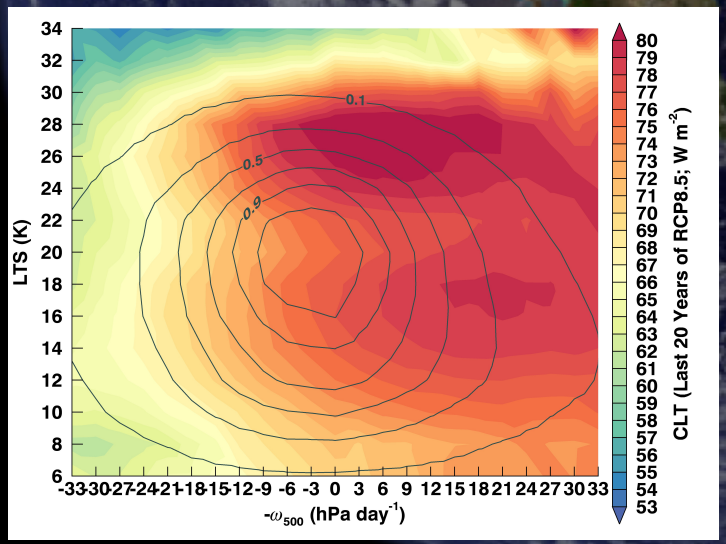
SW CRE becomes more negative in the higher LTS conditions

Annual mean change in Total Cloud Fraction:

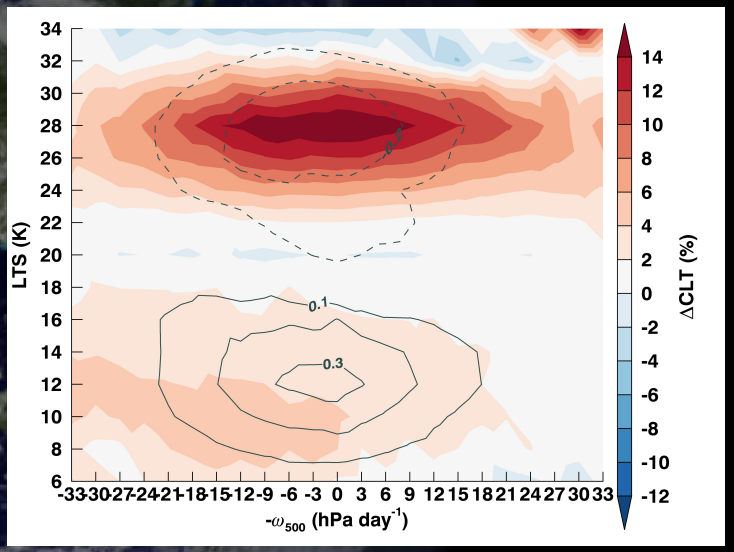
First 20 Years of RCP8.5



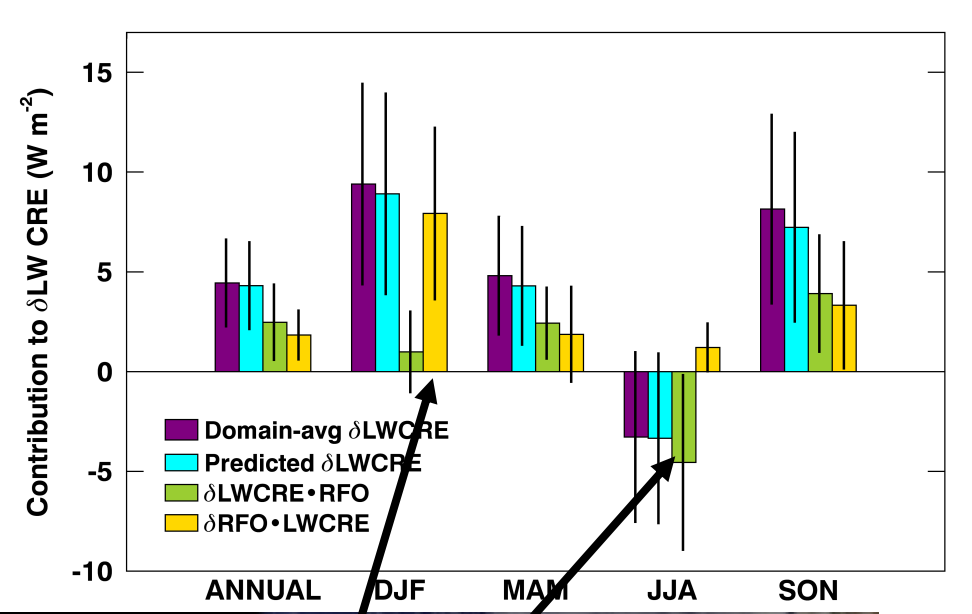
Last 20 Years of RCP8.5



Difference (Last 20 – First 20 years)

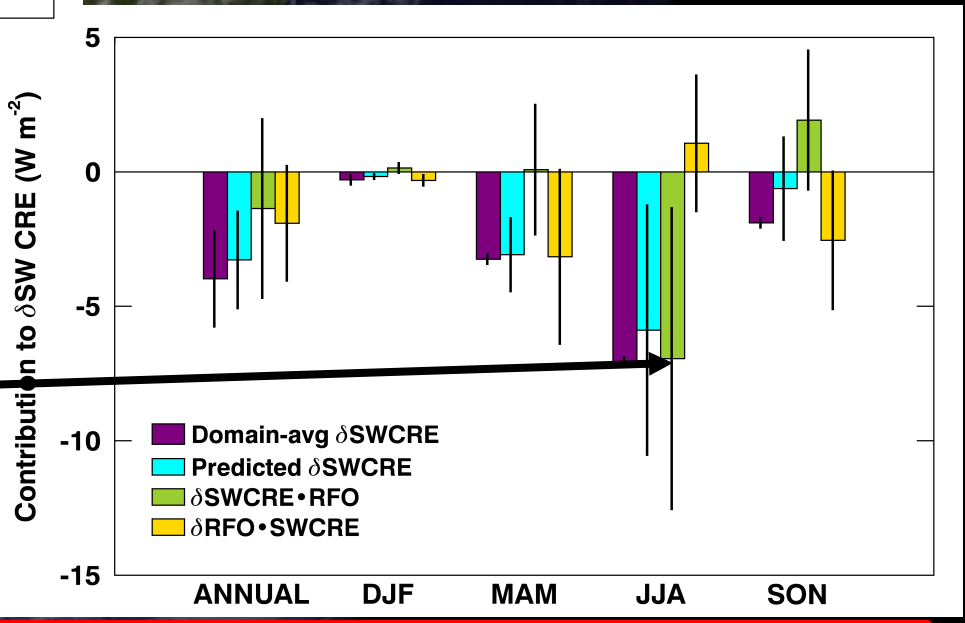


Contributions to CRE changes: Ensemble mean



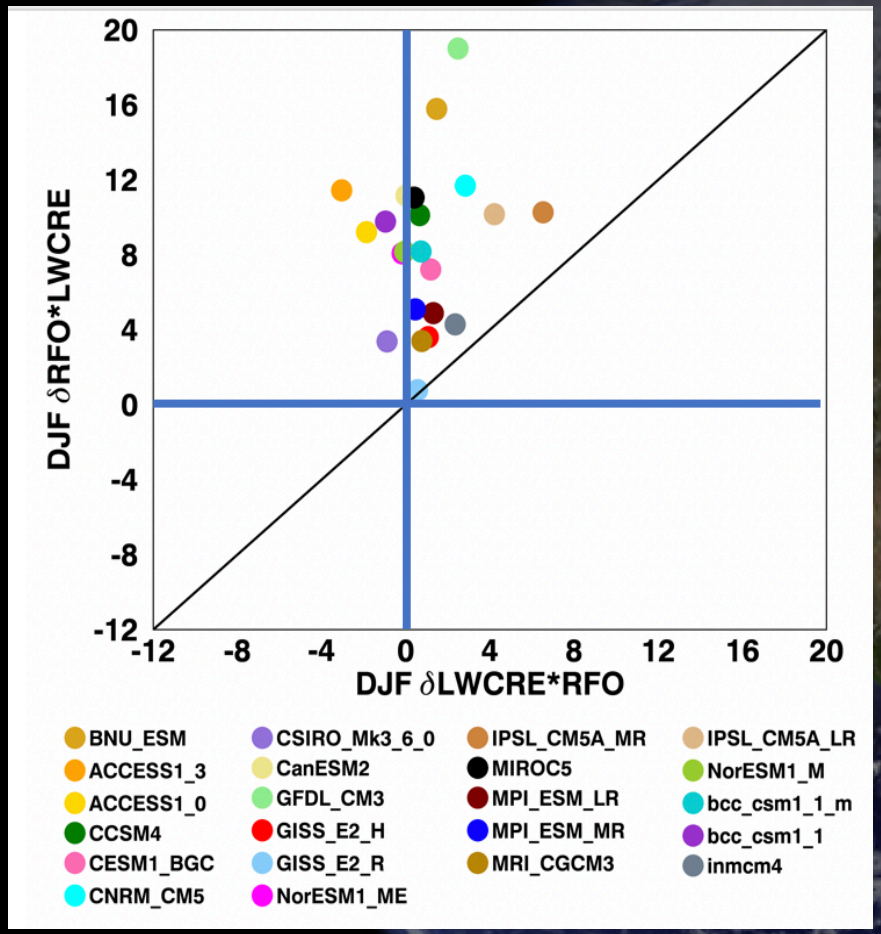
- Contributions from the two terms are similar in the annual mean.
- Individual seasons, however, show very large contributions from individual terms.

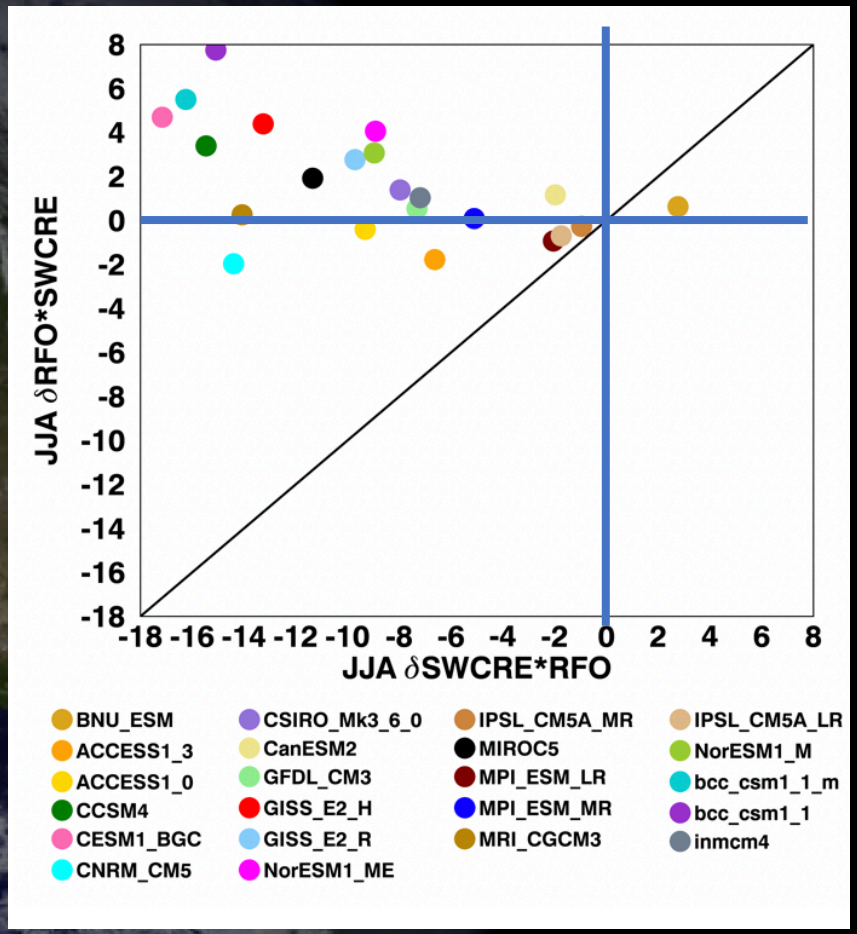
- For LWCRE, DJF shows a dominant contribution form the change in atmospheric regime frequency.
- In JJA, both LW CRE and SW CRE are dominated by a change in the joint PDF.



Contributions from a change in the atmospheric regime frequency or the CRE simulated within a regimes simulated CRE changes varies with season.

Contributions to CRE changes: Individual models





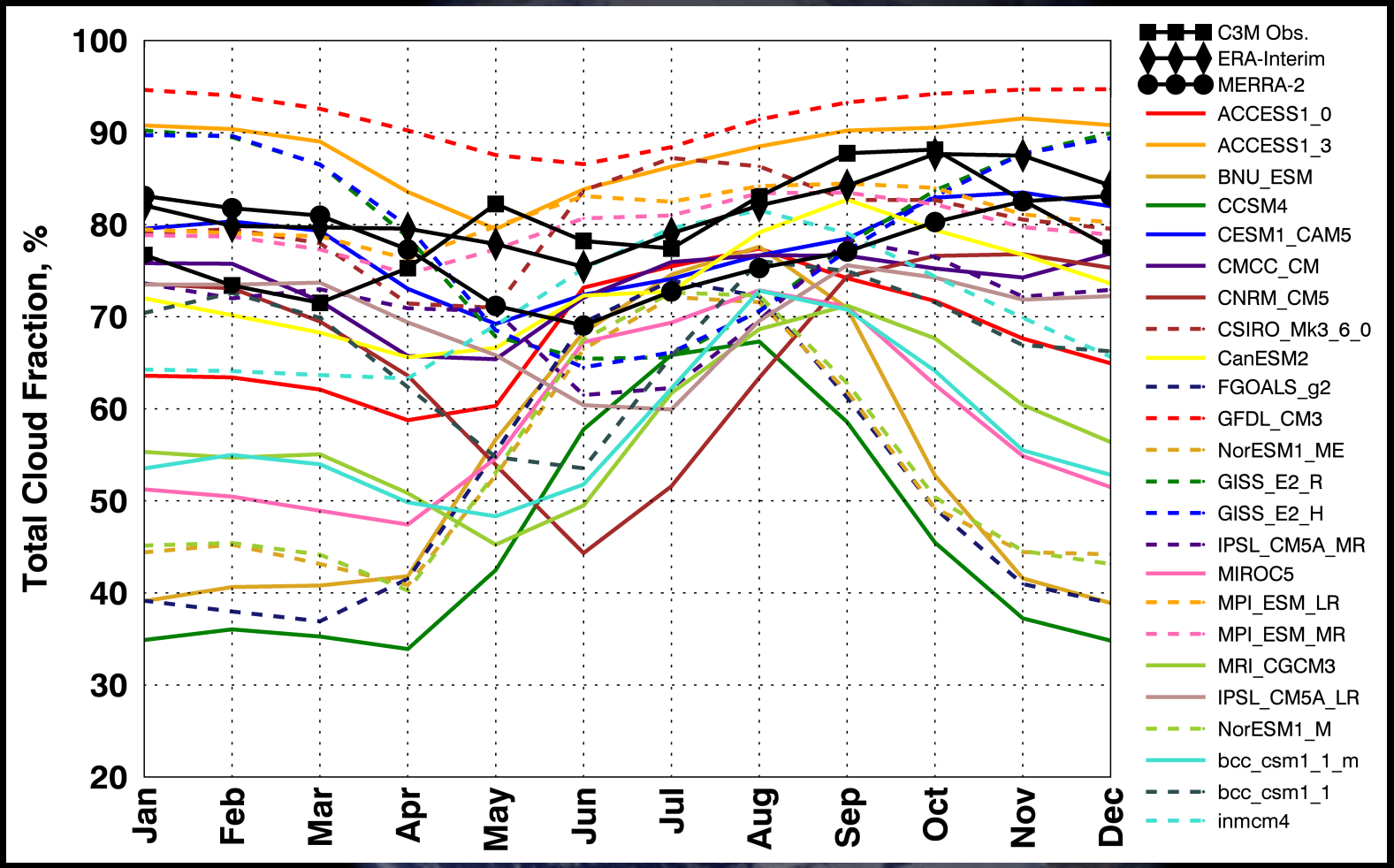
Individual models show significant differences in the contributions to the LW CRE and SW CRE changes

Takeaways…

- The cloud properties within atmospheric regimes is most important for explaining the seasonality of LW and SW CRE.
- Therefore to understand the seasonality of CRE in the Arctic is it critical that we understand how the linkages between clouds and meteorology change with season.
- Models exhibit much larger differences in the CRE within atmospheric regimes between the seasons than is found in CERES.

Thanks.

Total cloud amount annual cycle…

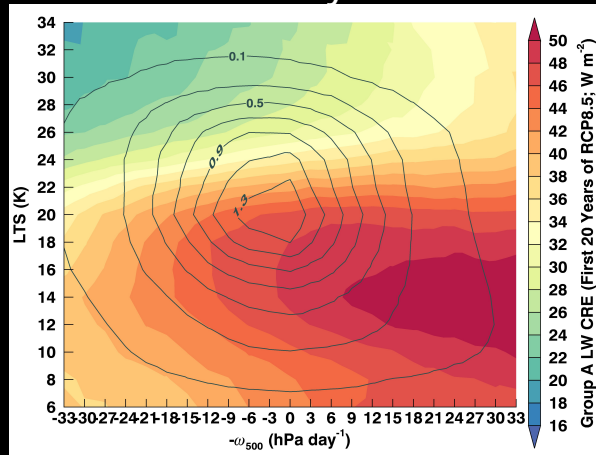


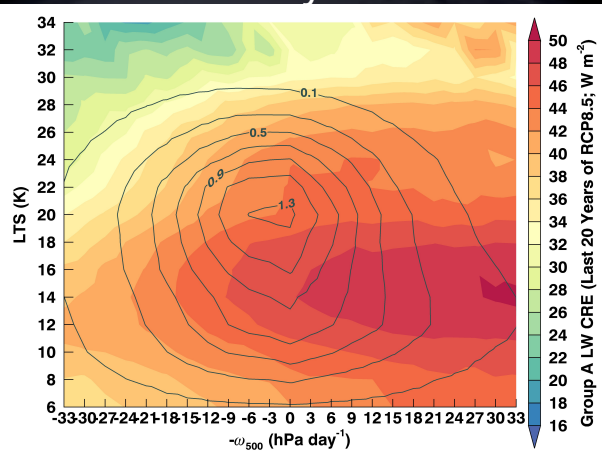
CMIP5 models significantly disagree on the Arctic cloud amount annual cycle.

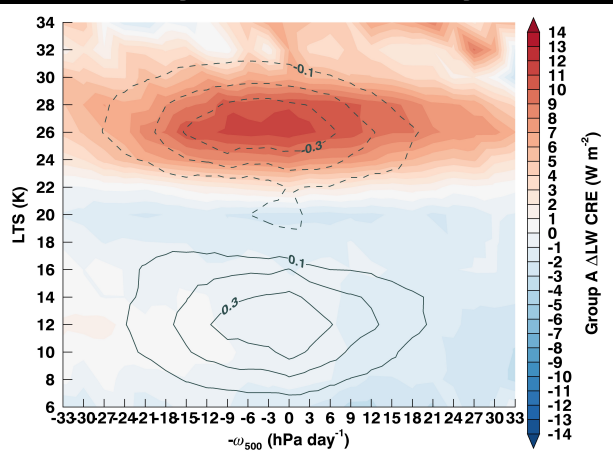
Group A and B LW CRE and projected changes (RCP8.5)

First 20 years | Last 20 years | Last 20 yrs – First 20 years

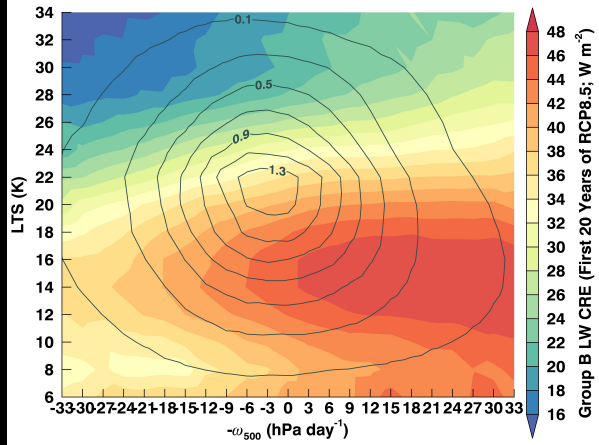
Group A

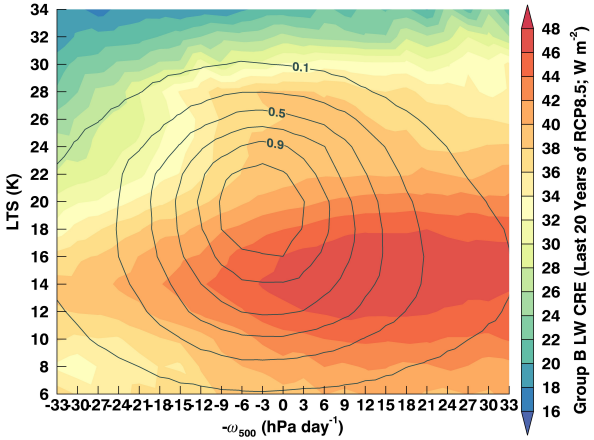


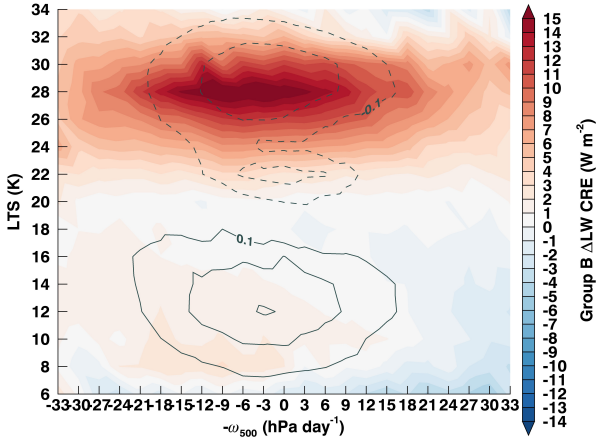




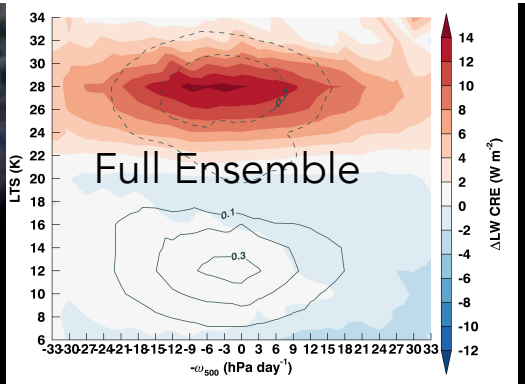
Group B







There are no substantial differences between the projected changes in LW CRE when stratifying by microphysical scheme.

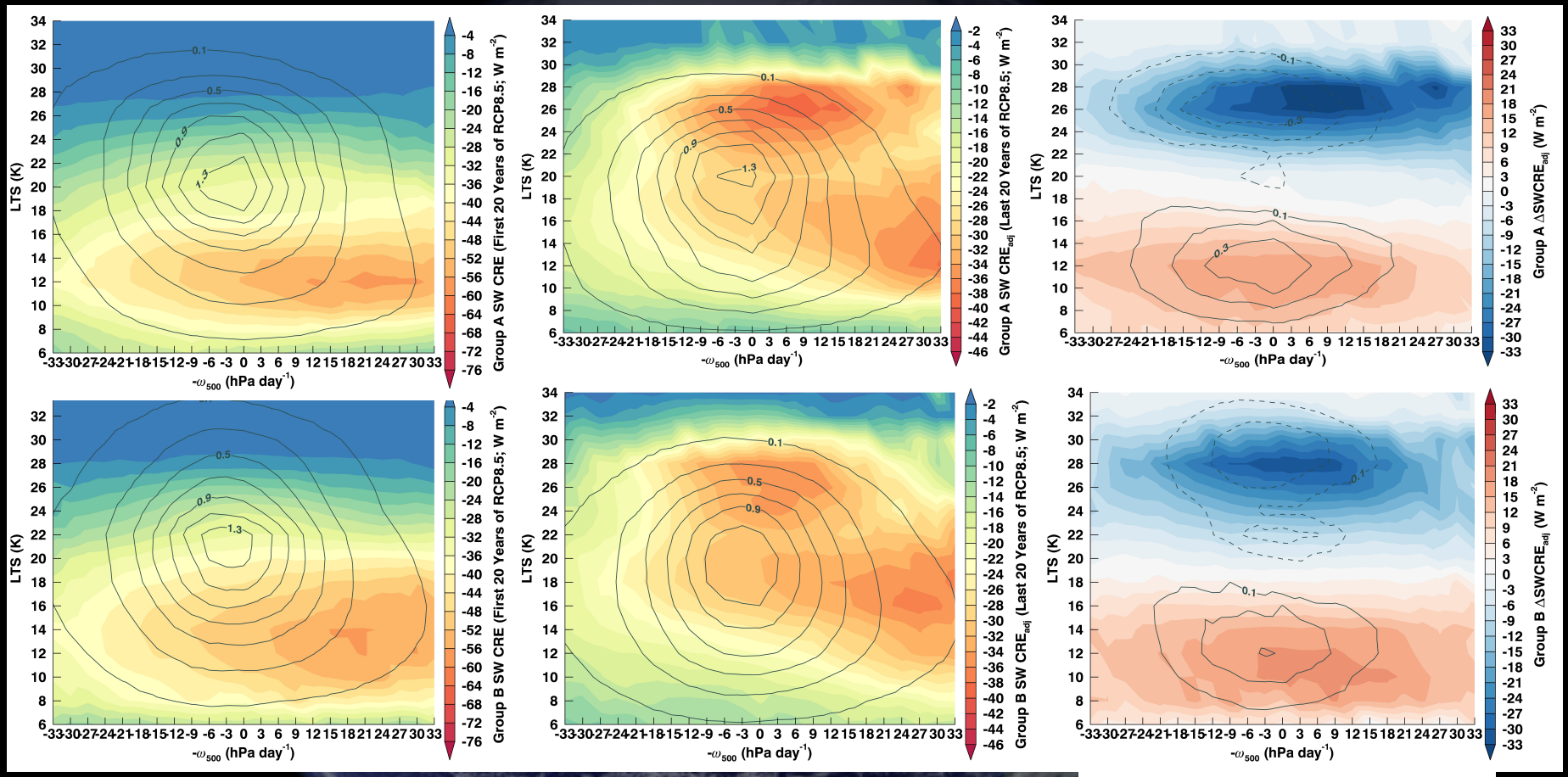


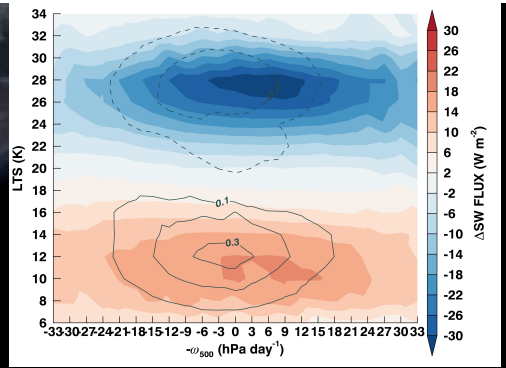
Group A and B SW CREadj and projected changes

First 20 years | Last 20 years | Last 20 yrs– First 20 yrs

Group A

Group B



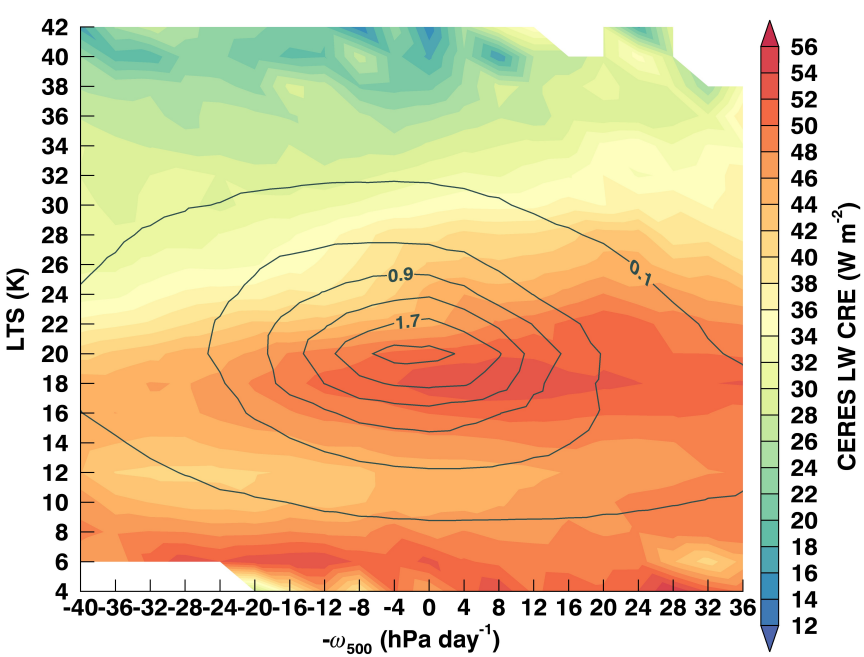


There are no substantial differences between the projected changes in SW CREadj when stratifying by microphysical scheme.

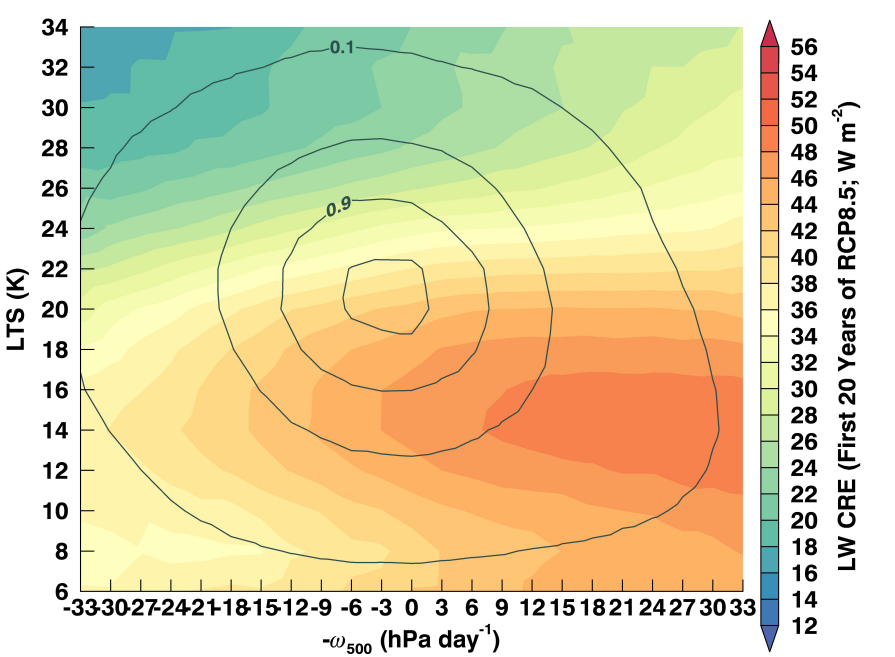
Regime Decomposition: LTS and Omega_500

Annual Mean LW CRE

CERES



CMIP5

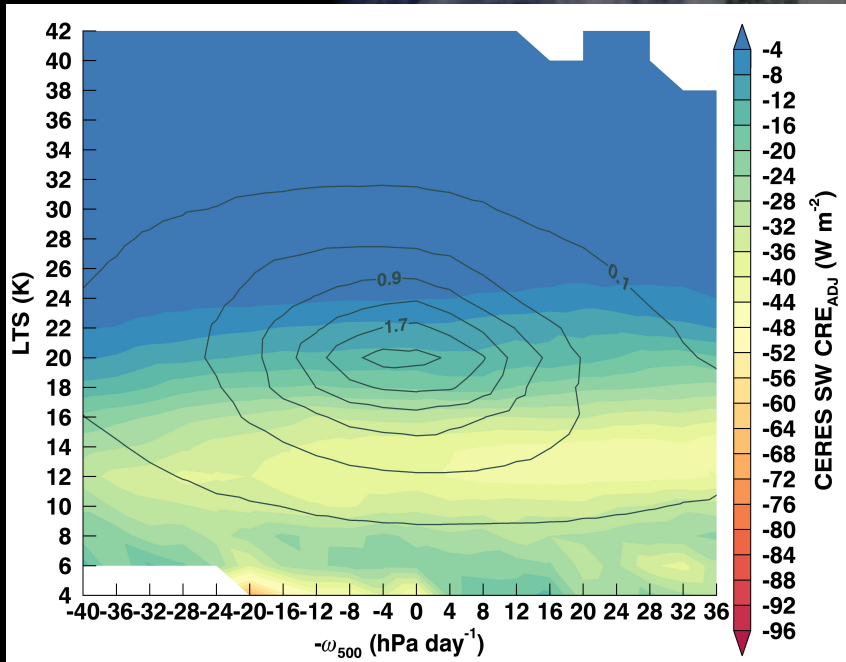


The CMIP5 model ensemble shows general agreement with CERES.

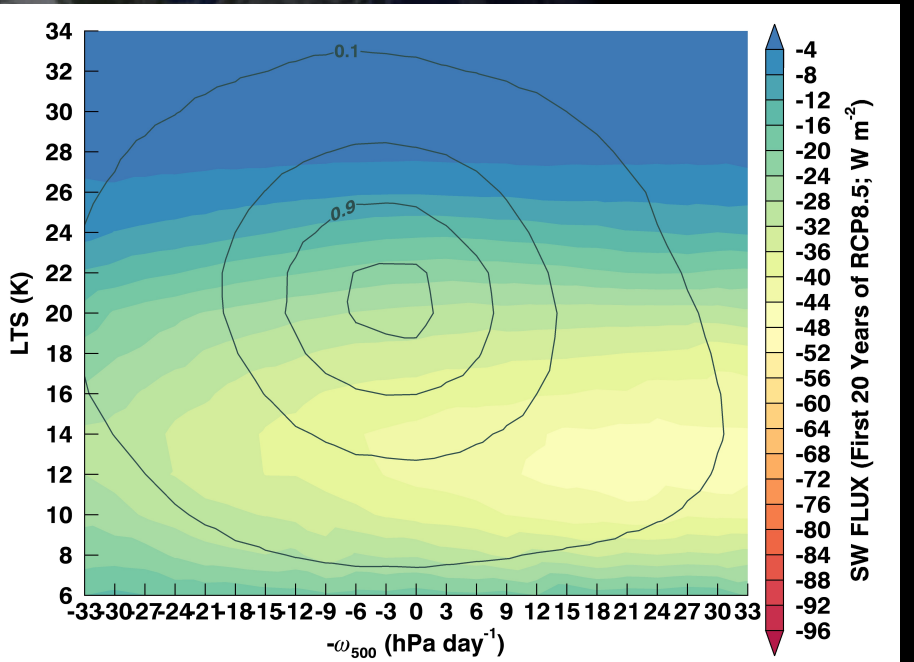
Regime Decomposition: LTS and Omega_500

Annual Mean SW CRE

CERES



CMIP5



The CMIP5 model ensemble shows general agreement with CERES.

Intergroup LCA differences: Regime frequency of occurrence or LCA joint PDF?

$$\overline{\delta LCA_{G1-G2}} = \sum_{i,j}\left[\left(\delta LCA\left(LTS_i, -\omega_{500,j}\right)_{G1-G2} * RFO\left(LTS_i, -\omega_{500,j}\right)_{G1}\right)\right] + \sum_{i,j}\left[\left(LCA\left(LTS_i, -\omega_{500,j}\right)_{G1} * \delta RFO\left(LTS_i, -\omega_{500,j}\right)_{G1-G2}\right)\right]$$

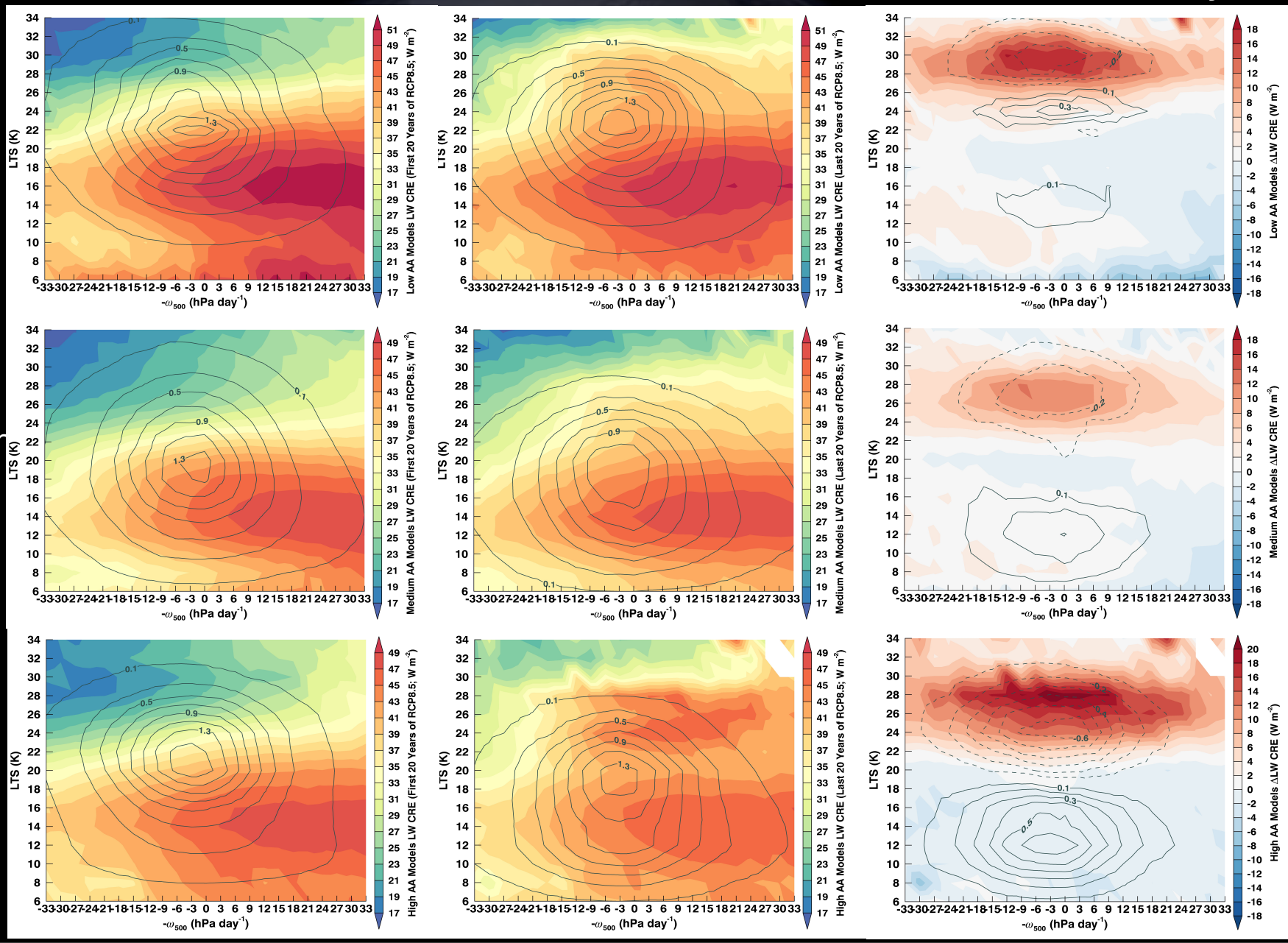
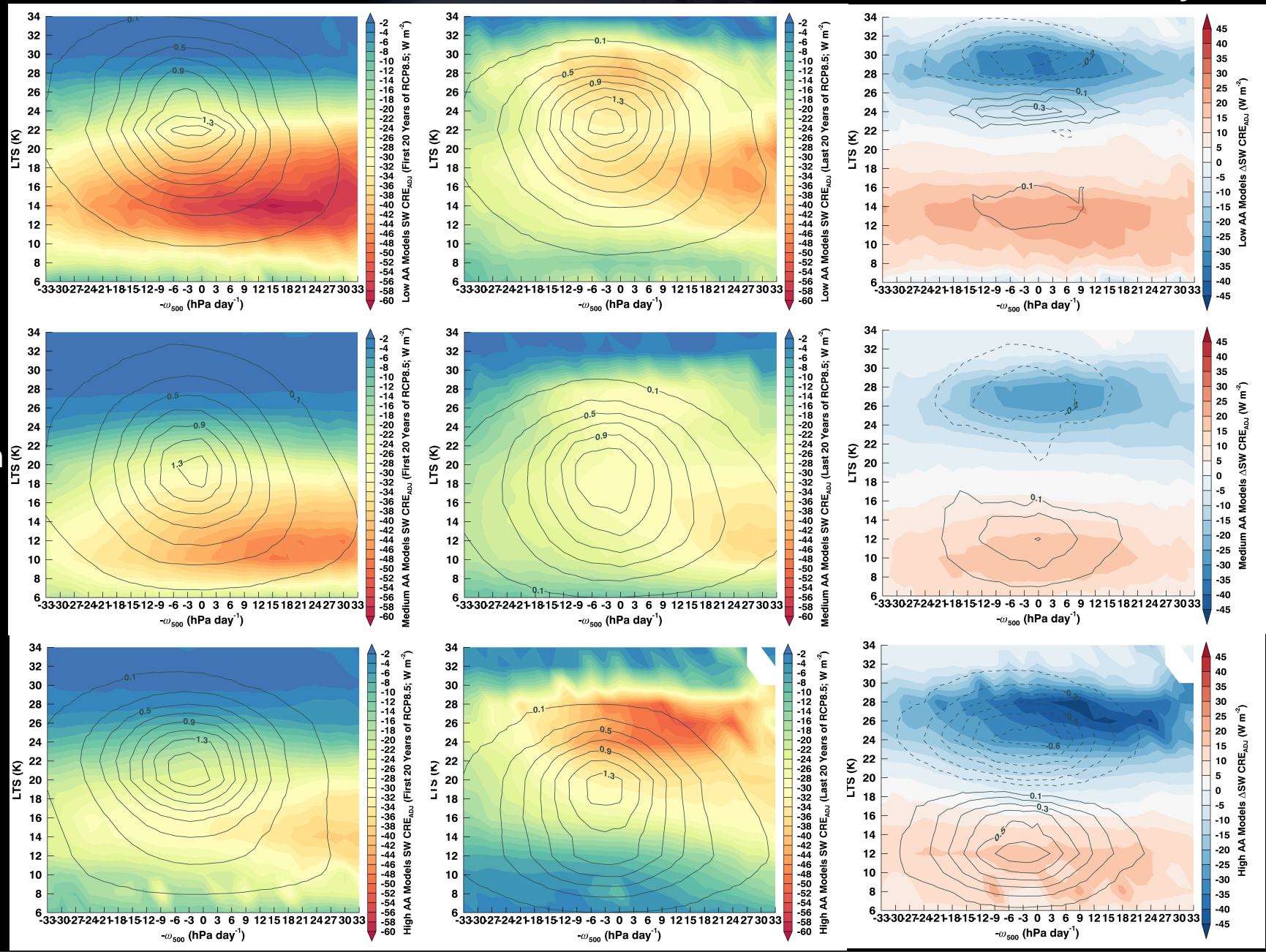
Term 1: δLCA due to δLCA(LTS, $-\omega_{500}$)

Term 2: δLCA due to δRFO

	Average LCA constructed from $(\mathrm{LTS}_i, -\omega_{500,j})$			
	$\overline{\Delta \mathrm{LCA}}_{\mathrm{G1-G2}}$	$\overline{\delta \mathrm{LCA}}_{\mathrm{G1-G2}}$	$\delta \mathrm{LCA}_{\mathrm{G1-G2}} \times \mathrm{RFO}_{\mathrm{G1}}$	$\mathrm{LCA}_{\mathrm{G1}} \times \delta \mathrm{RFO}_{\mathrm{G1-G2}}$
Winter	11.80 %	13.30 %	13.10 %	0.17 %
Summer	−3.84 %	−4.45 %	−4.49 %	0.05 %
	Average LCA constructed from $(T_{\mathrm{a},i}, \mathrm{RH}_j)$			
	$\overline{\Delta \mathrm{LCA}}_{\mathrm{G1-G2}}$	$\overline{\delta \mathrm{LCA}}_{\mathrm{G1-G2}}$	$\delta \mathrm{LCA}_{\mathrm{G1-G2}} \times \mathrm{RFO}_{\mathrm{G1}}$	$\mathrm{LCA}_{\mathrm{G1}} \times \delta \mathrm{RFO}_{\mathrm{G1-G2}}$
Winter	11.60 %	10.40 %	12.20 %	−1.80 %
Summer	−4.20 %	−4.68 %	−1.37 %	−3.31 %

Group differences are overwhelmingly attributed to the δLCA(LTS, $-\omega_{500}$) term, differences in the LCA produced within each regime (e.g., cloud parameterization). Results differ by the definition of atmospheric regime.

Annual mean LW CRE changes stratified by AA factor



Annual mean SW CRE changes stratified by AA factor