Decomposition of CRE interannual variability with the FluxByCldTyp dataset

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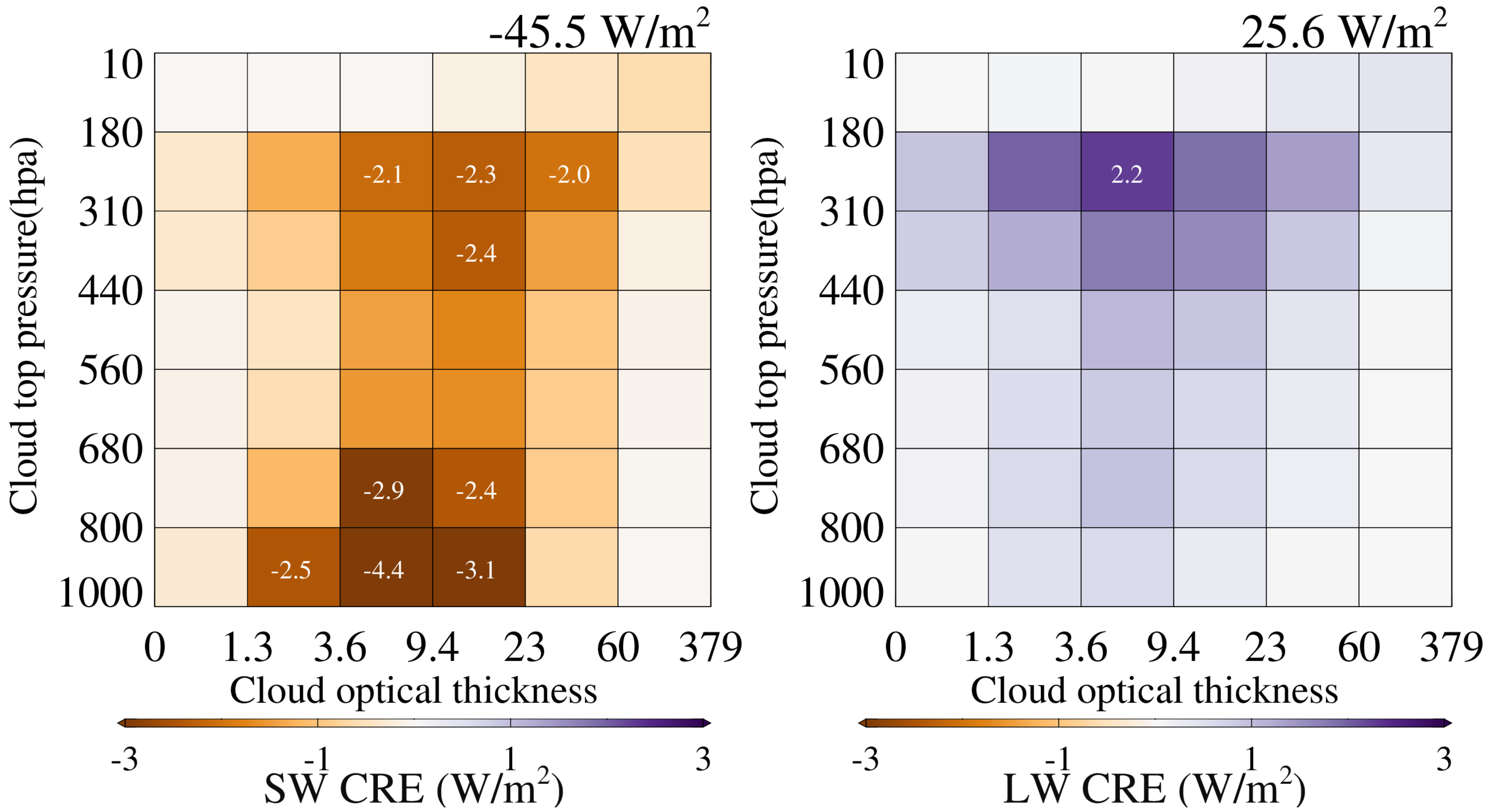
Spring 2023 CERES Science Team Meeting

Why FluxByCldTyp (FBCT)?

- Resolves the (subgrid) details of $\boldsymbol{CRE = F_{all-sky} - F_{clr}}$
- 1° $\boldsymbol{CRE = F_{all-sky} - F_{clr}}$ comes from contribution of many clouds within a grid cell and FBCT resolves these subgrid details.
- Provides a $\boldsymbol{CRE}$ array $\boldsymbol{CRE(i), i = 1, 42}$ ($\boldsymbol{7\ CTP\ and\ 6\ TAU\ bins}$)
  - GCMs typically do not provide subgrid CRE
- Allows us to examine the contribution of different cloud "types" (as defined by $\boldsymbol{CTP - TAU}$ combinations) to $\boldsymbol{CRE}$ at various spatiotemporal scales.
- See for example the global SW and LW $\boldsymbol{\widetilde{CRE(i)}}$ from monthly FBCT…

Global SW and LW $\widetilde{CRE}(i)$ from monthly FBCT, 2003-2019

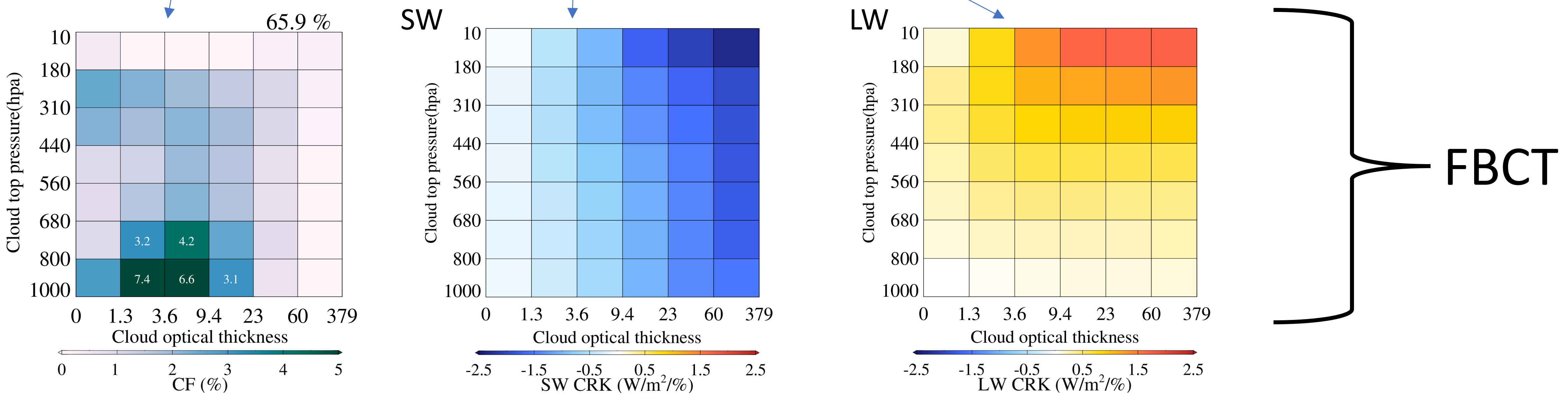


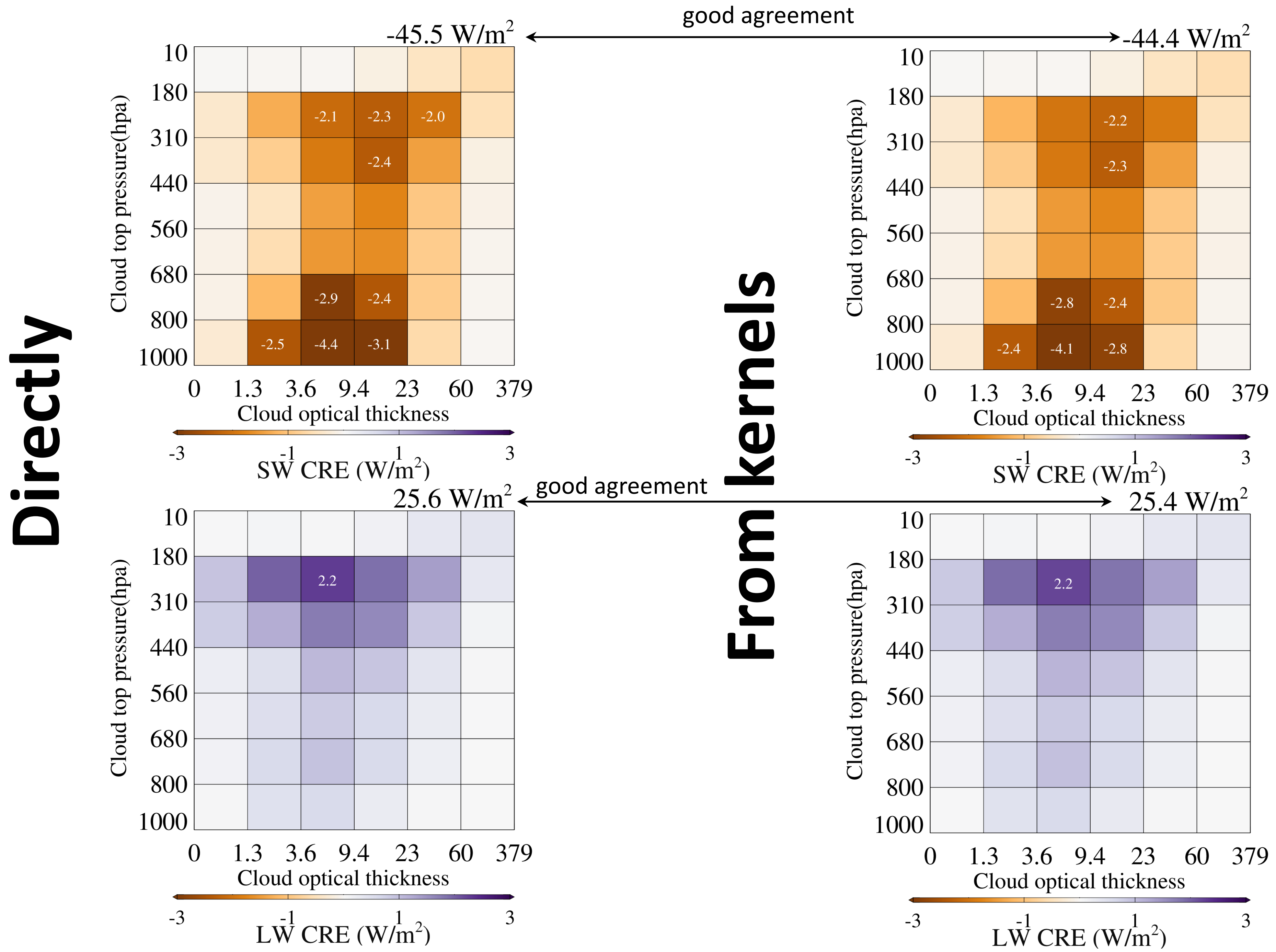
Cloud Radiative Kernels

- Following Zelinka et al. (2012) one can view $CRE(i)$ as the product of cloud fraction array $C(i), i = 1, 42$ and a "Cloud Radiative Kernel" CRK ($K(i)$)

  $K(i) \equiv \left(F_{ovc}(i) - F_{clr}(i)\right)/100$ (often assuming that $F_{clr}(i) = \text{grid cell mean } F_{clr}$)

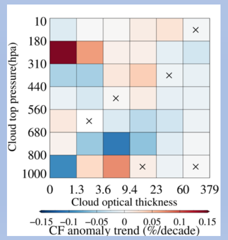
- $CRE(i) = C(i) \times K(i)$
- But a single *global* $\widetilde{C(i)}$ multiplied by a single *global* $\widetilde{K(i)}$ does not give correct $\widetilde{CRE(i)}$
- Resolving $K(i)$ by latitude and month helps: obtain then global $\widetilde{CRE(i)}$ by averaging zonal values of $C(i)\times\overline{K(i)}$, $\widetilde{CRE(i)} \approx \widetilde{C(i)\times\overline{K(i)}}$
- One expects $K(i)$ to be somewhat sensitive to binning choice
- The Zelinka $CRKs$ came from off-line RT computations; FBCT provides observed $CRKs$ (see also Sun et al. 2022)



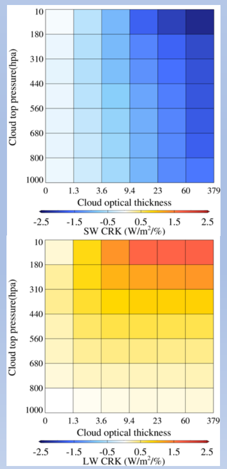

good agreement
-45.5 W/m²
-44.4 W/m²
Directly
From kernels
Cloud top pressure(hpa)
10
180
310
440
560
680
800
1000
0
1.3
3.6
9.4
23
60
379
Cloud optical thickness
-2.1
-2.3
-2.0
-2.4
-2.9
-2.4
-2.5
-4.4
-3.1
-2.2
-2.3
-2.8
-2.4
-2.4
-4.1
-2.8
-3
-1
1
3
SW CRE (W/m²)
good agreement
25.6 W/m²
25.4 W/m²
2.2
2.2
LW CRE (W/m²)

Why is this concept useful?

- We can examine ***why*** CRE changes.
- The CRK is meant to be a fundamental property capturing the sensitivity of CRE to cloud changes for given certain atmospheric and surface conditions.
- To first order, ΔCRE anomalies may be driven by changes in the cloud fraction array $C(i)$ i.e., cloud amount changes within $CTP - TAU$ bins which reflect changes in C_{tot}, and/or mean CTP, TAU.
- It is thus tempting to interpret $CRE(i)$ anomalies $\Delta CRE(i)$ in terms of $C(i)$ anomalies $\Delta C(i)$: $\Delta CRE(i) \approx \Delta C(i) \times K(i)$.



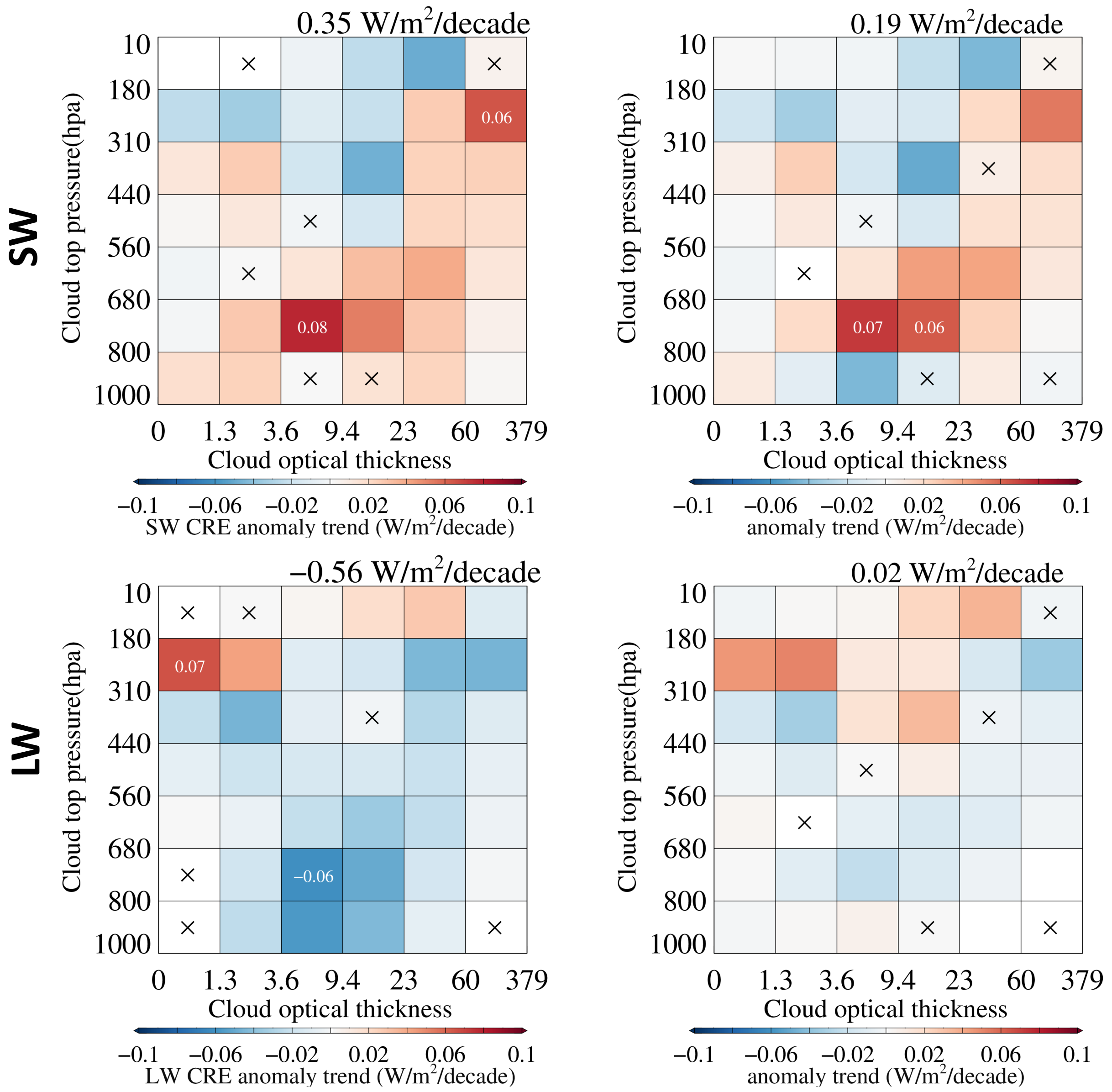
×



- FBCT allows us to calculate $\Delta CRE(i)$ either directly, or through the kernel method.

2003-2019

directly calculated ΔCRE $\neq$ from cloud anomaly $\Delta C \times \overline{K}$

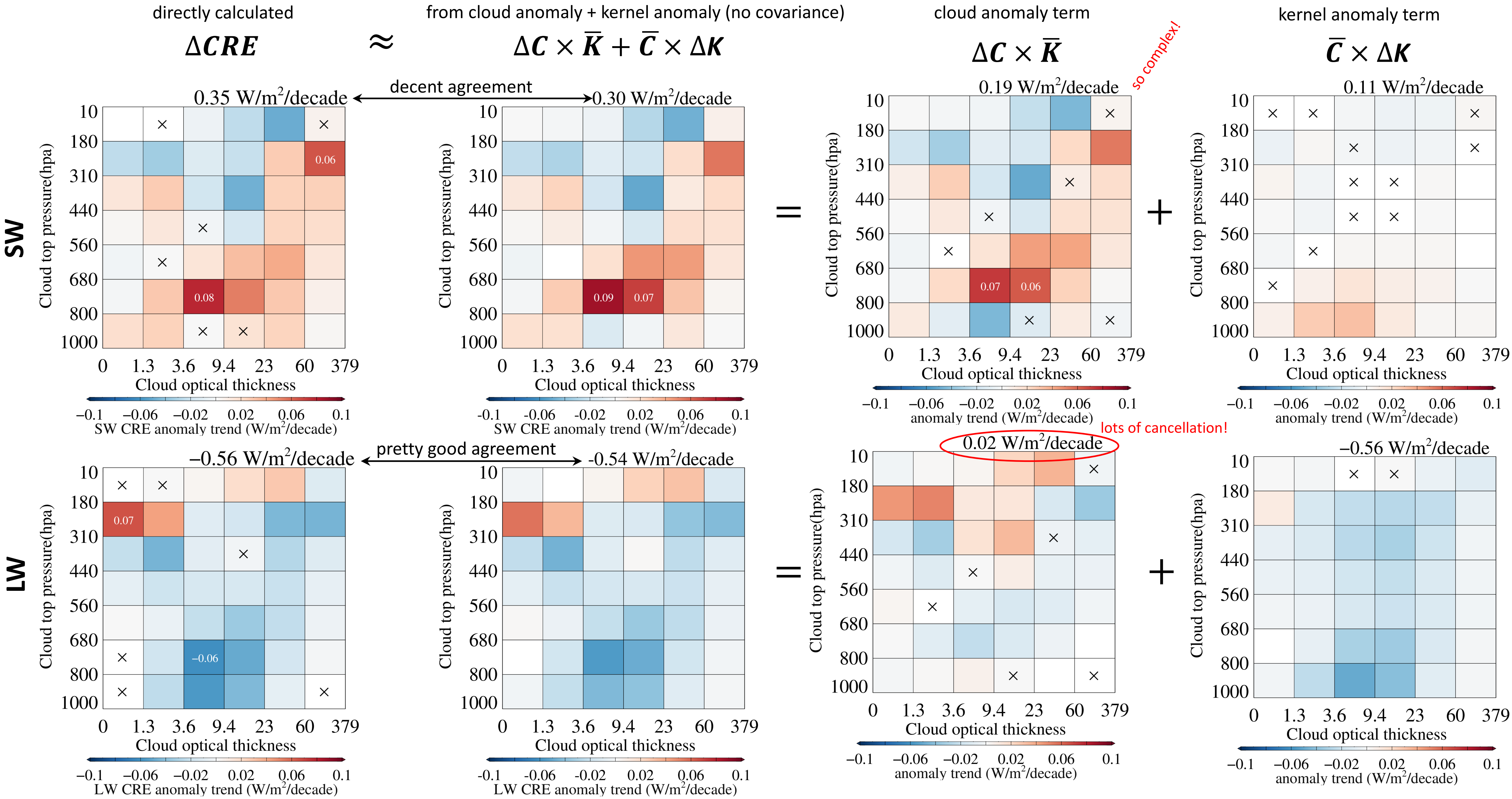


While $\widetilde{CRE(i)} \approx \widetilde{C(i) \times \overline{K(i)}}$, the first-order approximation $\Delta\widetilde{CRE(i)} \approx \Delta\widetilde{C(i)} \times \overline{K(i)}$ does not appear to hold.

$\overline{K(i)}$ changes need to be taken into account!

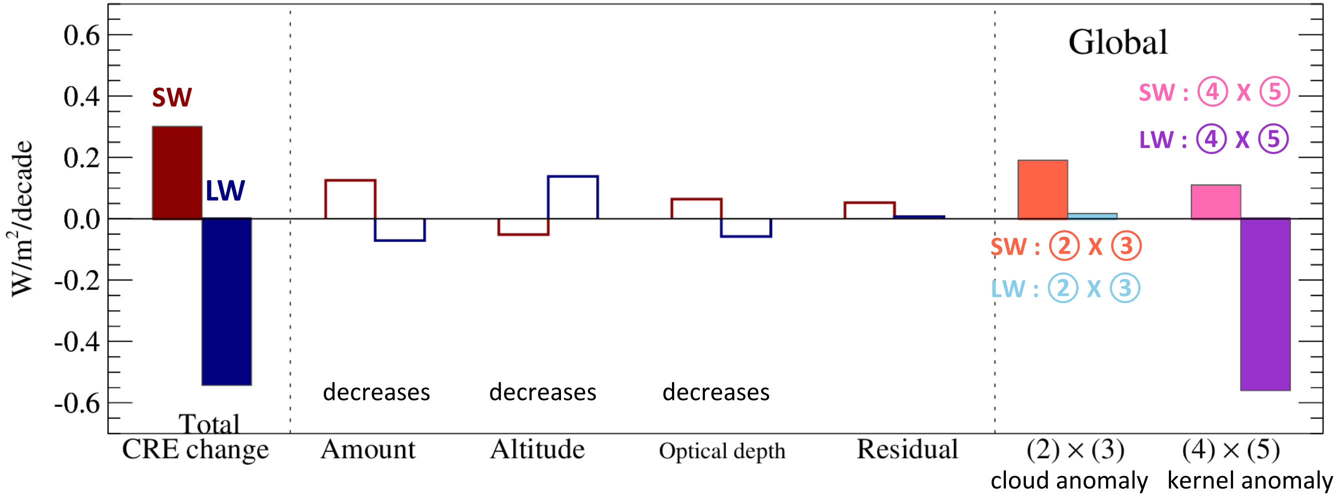
(simplified notation)

$$\Delta CRE = \underbrace{\Delta C \times \overline{K}}_{\text{cloud anomaly}} + \underbrace{\overline{C} \times \Delta K}_{\text{kernel anomaly}} + covariance$$


directly calculated
ΔCRE
≈
from cloud anomaly + kernel anomaly (no covariance)
ΔC × K̄ + C̄ × ΔK
=
cloud anomaly term
ΔC × K̄
+
kernel anomaly term
C̄ × ΔK
so complex!
SW
0.35 W/m2/decade
decent agreement
0.30 W/m2/decade
0.19 W/m2/decade
0.11 W/m2/decade
Cloud top pressure(hpa)
10
180
310
440
560
680
800
1000
0
1.3
3.6
9.4
23
60
379
Cloud optical thickness
0.06
0.08
0.09
0.07
0.07
0.06
−0.1
−0.06
−0.02
0.02
0.06
0.1
SW CRE anomaly trend (W/m2/decade)
anomaly trend (W/m2/decade)
LW
−0.56 W/m2/decade
pretty good agreement
-0.54 W/m2/decade
lots of cancellation!
0.02 W/m2/decade
−0.56 W/m2/decade
0.07
−0.06
LW CRE anomaly trend (W/m2/decade)

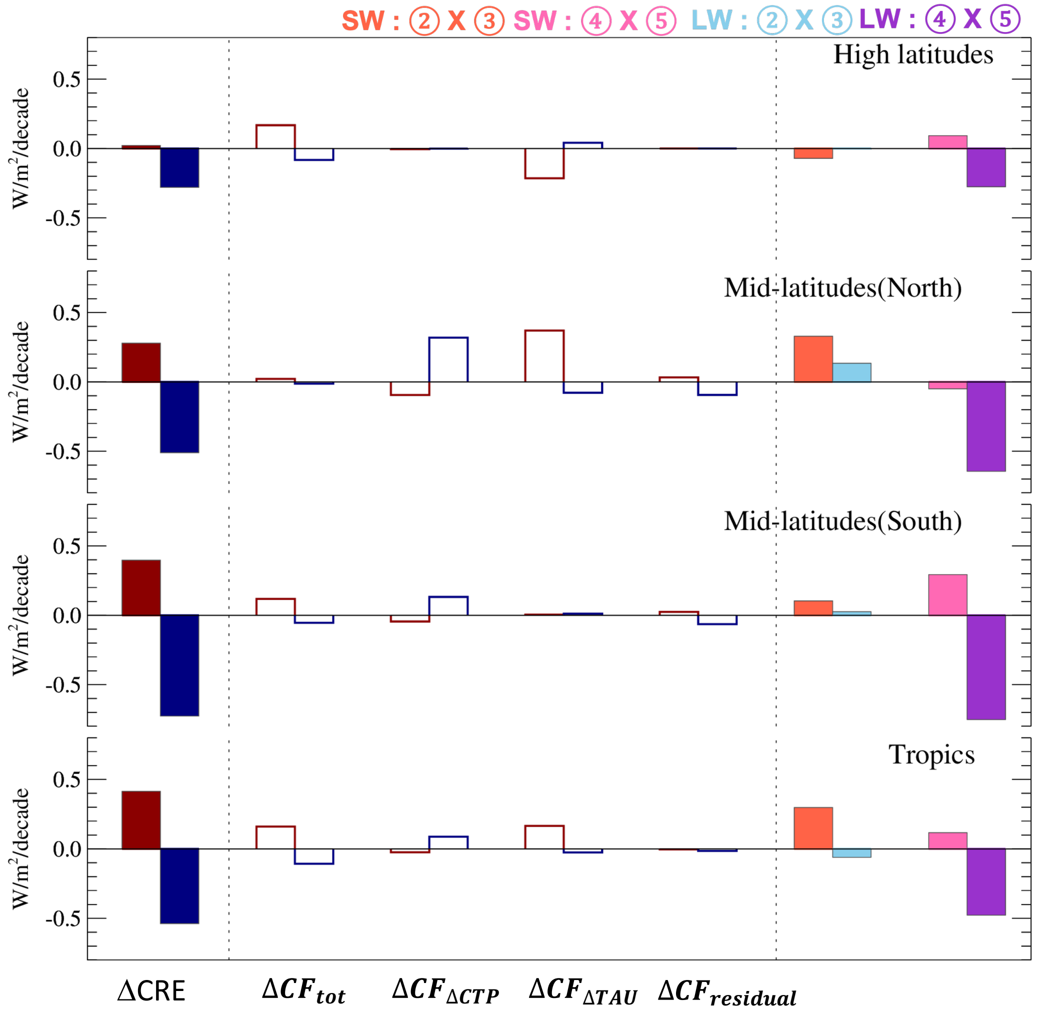
A closer look at the cloud anomaly term "② × ③"

$$\overset{①}{\Delta CRE} \approx \overset{②}{\Delta C} \times \overset{③}{\bar{K}} + \overset{④}{\bar{C}} \times \overset{⑤}{\Delta K}$$



$$\Delta C = \Delta C_{tot} + \Delta C_{\Delta CTP} + \Delta C_{\Delta TAU} + \Delta C_{residual}$$

Methodology : Zelinka et al., 2013



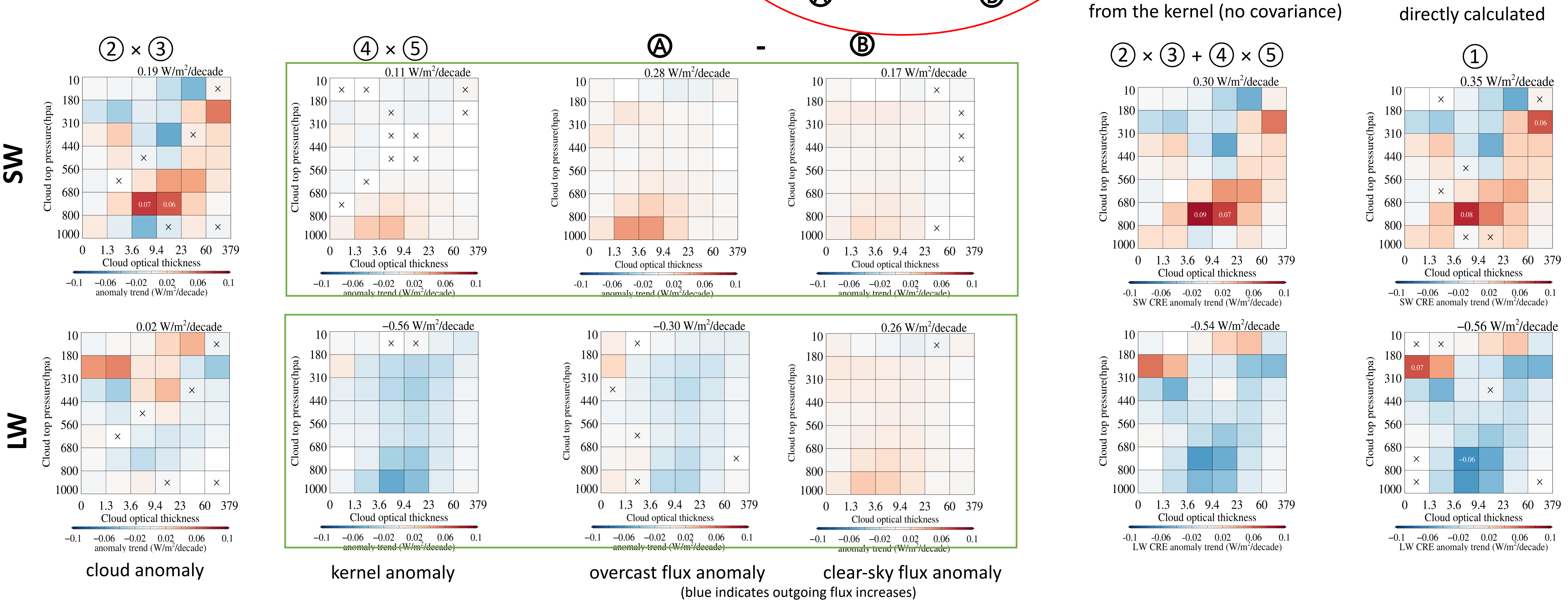
2003-2019

A closer look at the kernel anomaly term “④ × ⑤”

$$\underset{①}{\Delta CRE} \approx \underset{②}{\Delta C} \times \underset{③}{\overline{K}} + \underset{④}{\overline{C}} \times \underset{⑤}{\Delta K}$$

$$\Delta CRE = \Delta C \times (\overline{F_{ovc} - F_{clr}}) + \overline{C} \times \Delta(F_{ovc} - F_{clr})$$

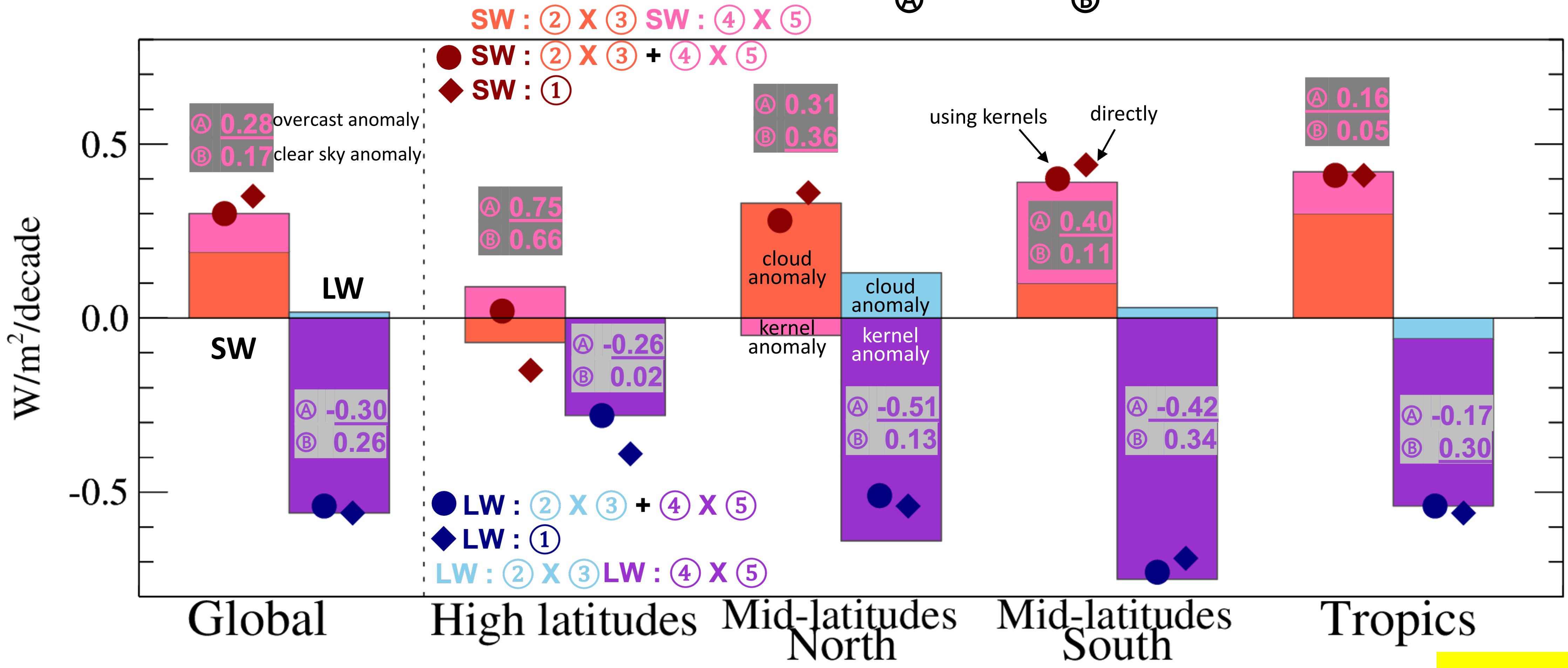
$$\Delta CRE = \Delta C \times (\overline{F_{ovc} - F_{clr}}) + \underset{Ⓐ}{\overline{C} \times \Delta F_{ovc}} - \underset{Ⓑ}{\overline{C} \times \Delta F_{clr}}$$



Everything together

$$\overset{①}{\Delta CRE} \approx \overset{②}{\Delta C} \times \overset{③}{\overline{K}} + \overset{④}{\overline{C}} \times \overset{⑤}{\Delta K}$$

$$\Delta CRE = \Delta C \times (\overline{F_{ovc} - F_{clr}}) + \underset{Ⓐ}{\overline{C} \times \Delta F_{ovc}} - \underset{Ⓑ}{\overline{C} \times \Delta F_{clr}}$$



2003-2019

Potential extension by breaking down by cloud class/type/regime

$$\Delta CRE = \sum_{k=0}^{K} \bar{f}_k \Delta C_k \bar{K}_k + \sum_{k=0}^{K} \bar{f}_k \bar{C}_k \Delta K_k + \sum_{k=0}^{K} \Delta f_k \bar{C}_k \bar{K}_k + covariance\ terms$$

②×③ — within regime (can break into $\Delta CF_{tot}, \Delta CF_{\Delta CTP}, \Delta CF_{\Delta TAU}$)

④×⑤ — within regime (can break into ovc and clr)

⑥ — across regimes

- In GCM work, Zelinka et al. (2022) considered only within-regime cloud anomaly ②×③ and between regime frequency change ⑥ terms.
- Have to use daily FBCT data because CRs are defined daily.
- Each CR has its own K, but their $\Delta K s$ appear noisy.

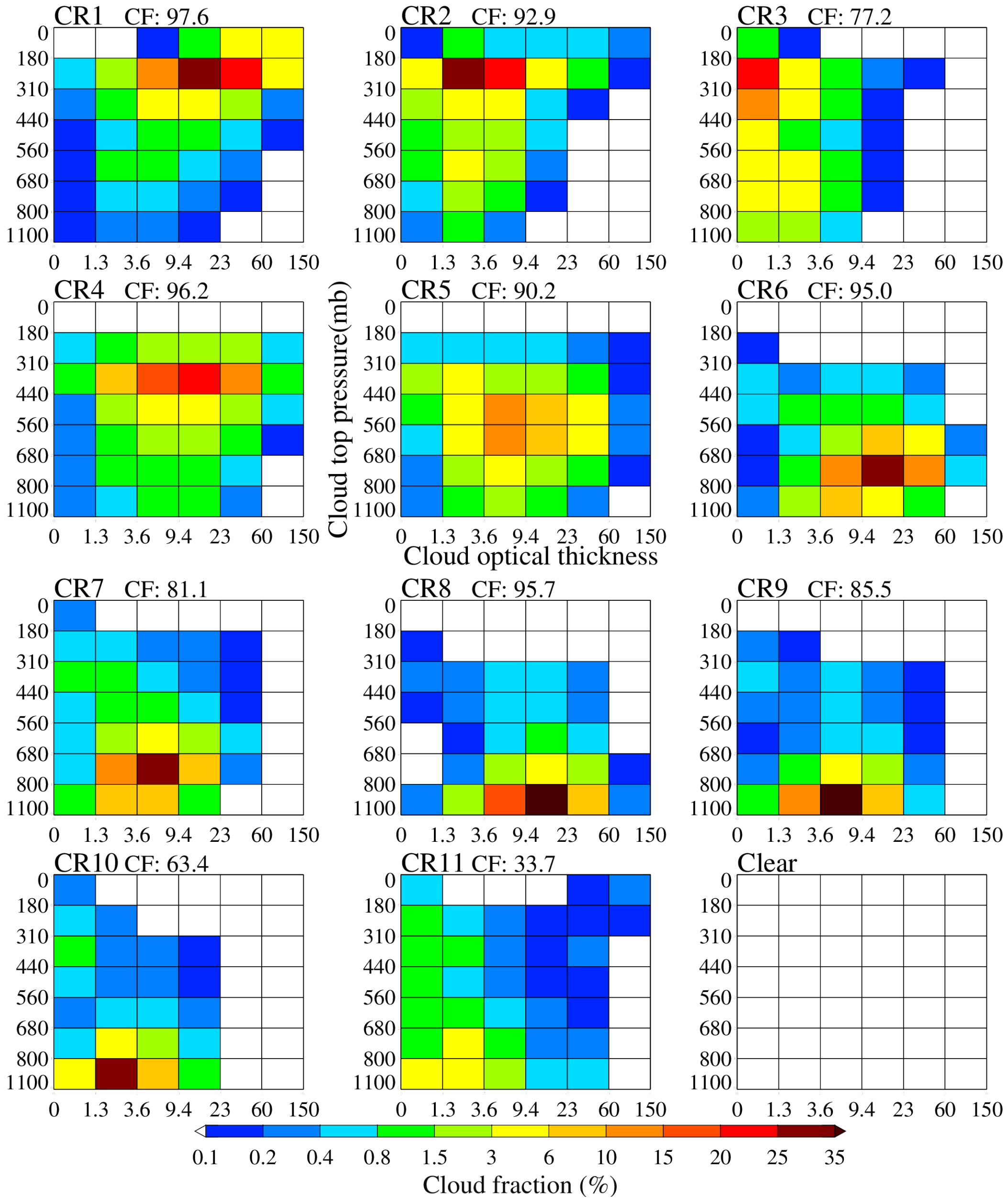
	Daily dataset	Wm^{-2}	decade^{-1}	Monthly dataset
	directly ($\Delta CRE = \sum_{k=0}^{K} \Delta CRE_k f_k$)	from equation above (no covariance)	directly	from cloud anomaly + kernel anomaly (no covariance)
SW	0.28	0.29	0.35	0.30
LW	-0.50	-0.45	-0.56	-0.54

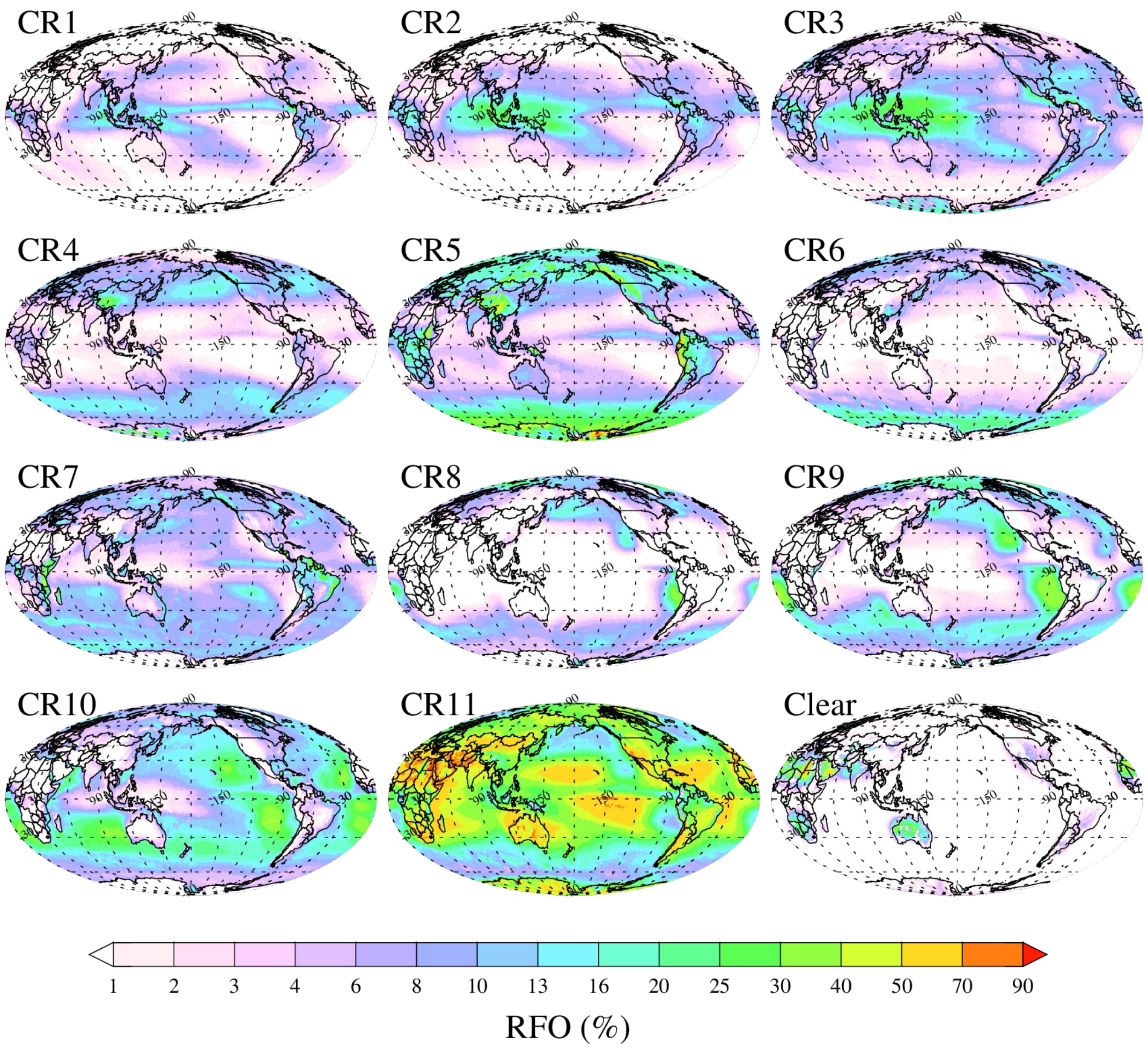
Conclusions

- CERES FBCT allows for a Cloud Radiative Kernel ($\boldsymbol{CRK}$) framework to be used to analyze and interpret $\boldsymbol{\Delta CRE}$.
- The first-order approximation of $\boldsymbol{\Delta CRE}$ coming from cloud changes and fixed CRKs cannot reproduce directly calculated $\boldsymbol{\Delta CRE}$.
- When $\boldsymbol{CRK}$ anomalies/trends are accounted for (i.e., anomalies in overcast and clear-sky fluxes) good global agreement between direct and kernel-based estimates of $\boldsymbol{\Delta CRE}$ is achieved.
- 2003-2019 analysis indicates a trend of weaker negative SW $\boldsymbol{CRE}$ values i.e., less cooling, and a trend of weaker positive values LW $\boldsymbol{CRE}$ values, i.e., less warming.
- A large contribution (~2/3) to SW $\boldsymbol{CRE}$ anomalies comes from fewer and optically thinner clouds, while LW $\boldsymbol{CRE}$ anomalies are dominated by overcast and clear-sky flux changes (i.e. $\boldsymbol{CRK}$ anomalies), as those due to cloud property anomalies largely cancel out.
    - Overcast (OVC) and clear sky (CLR) flux anomalies merit further investigation. LW outgoing fluxes increase for OVC and decrease for CLR (decreased LW $\boldsymbol{CRE}$); SW outgoing fluxes decrease more for OVC than CLR (decreased SW $\boldsymbol{CRE}$).

Backup Slides

CERES FBCT CRs

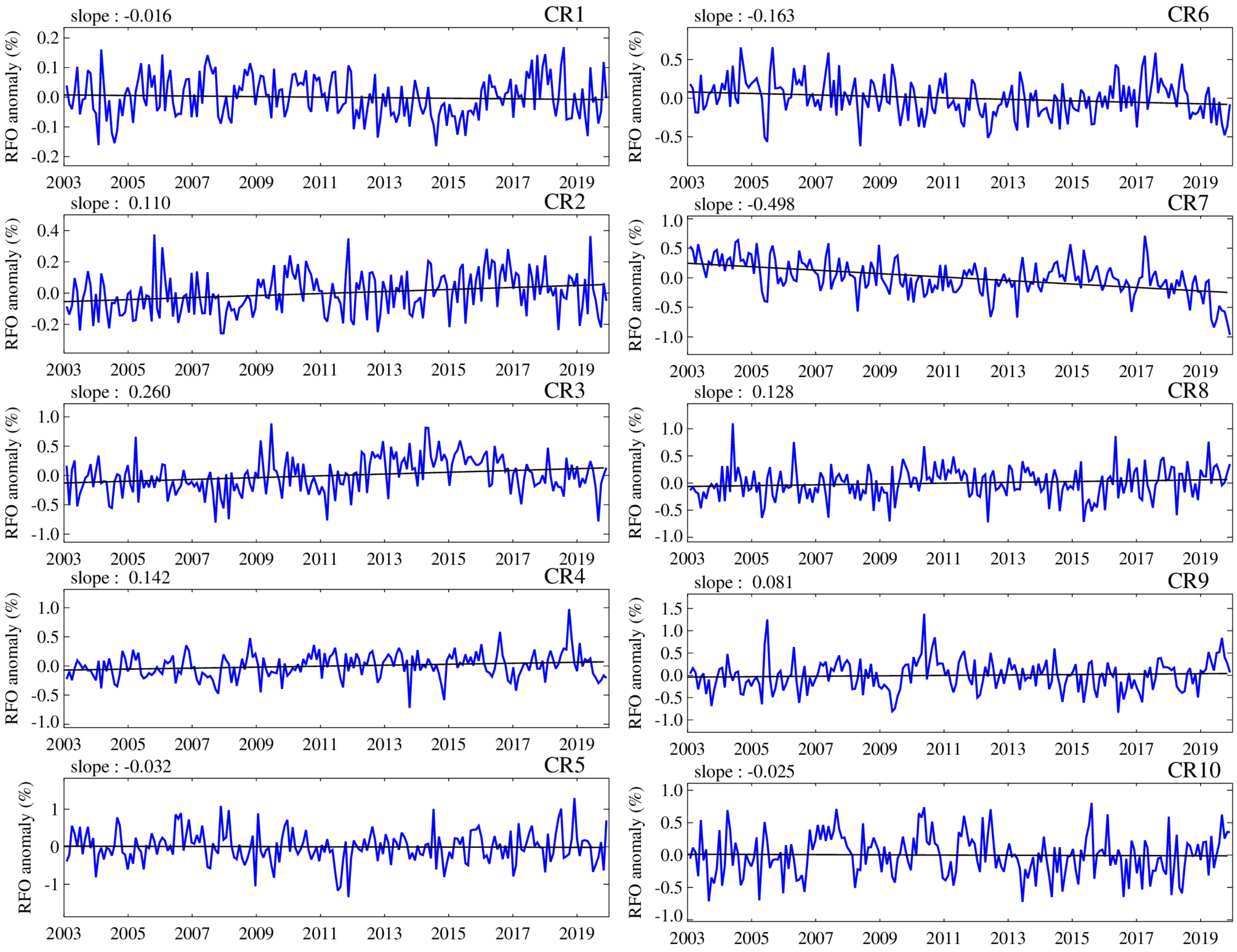


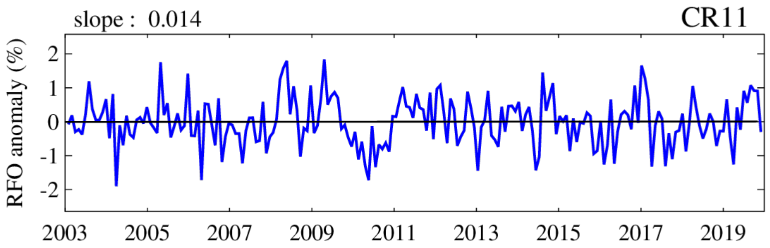


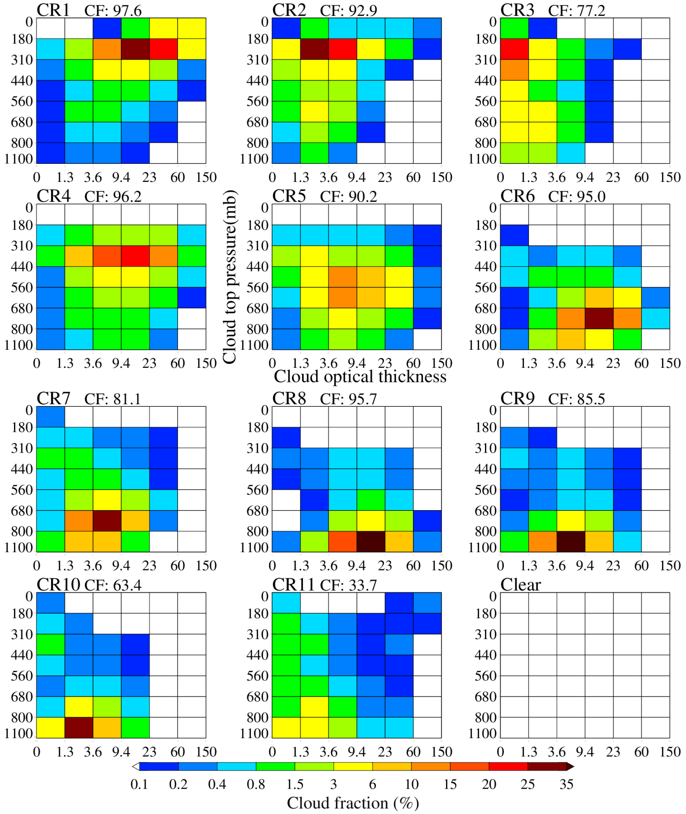
Daily dataset

$$\Delta CRE = \sum_{k=0}^{K} \left(\bar{f}_k \Delta C_k + \Delta f_k \bar{C}_k\right)\left(\bar{F}_k^{ovc} - \bar{F}_k^{clr}\right) + \sum_{k=0}^{K} \bar{f}_k \bar{C}_k \left(\Delta F_k^{ovc} - \Delta F_k^{clr}\right)$$

Check RFO trends for FBCT CRs, Δf_k (To confirm FBCT CRs have similar trends with MODIS CRs)





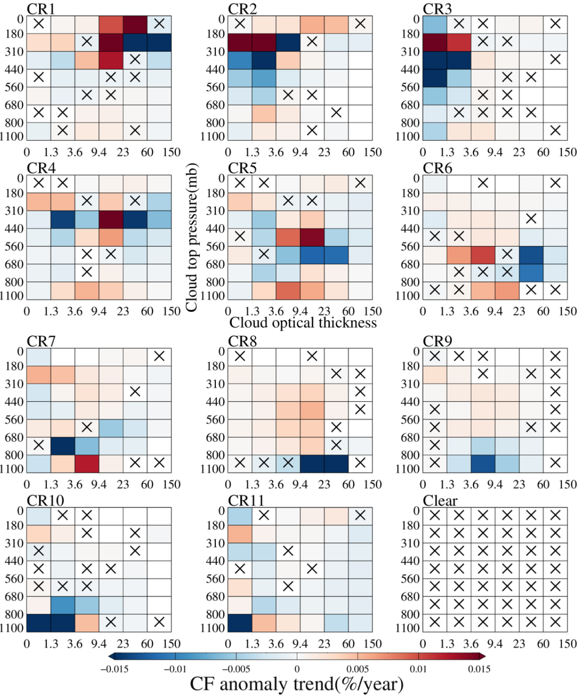


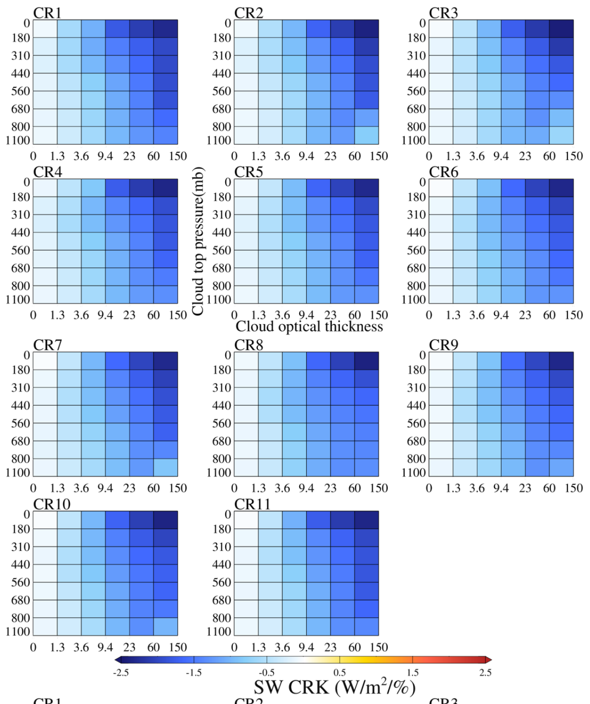
$\bar{f}_k$

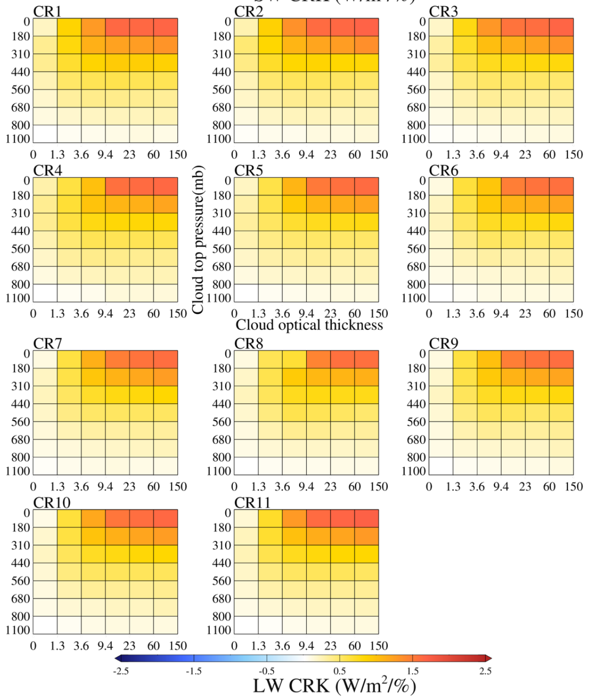
CR1:0.03
CR2:0.04
CR3:0.07
CR4:0.06
CR5:0.13
CR6:0.05
CR7:0.07
CR8:0.04
CR9:0.07
CR10:0.10
CR11:0.33
clear:0.01

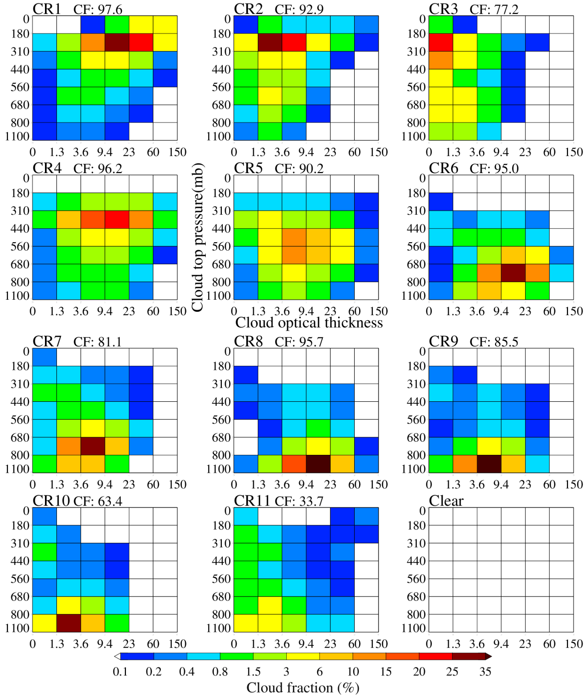
Supplementary slide (details) for slide 7

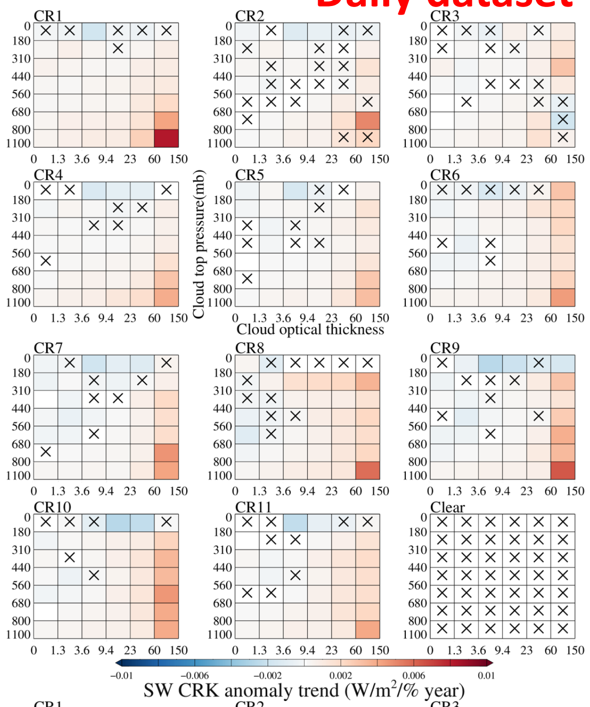
Daily dataset

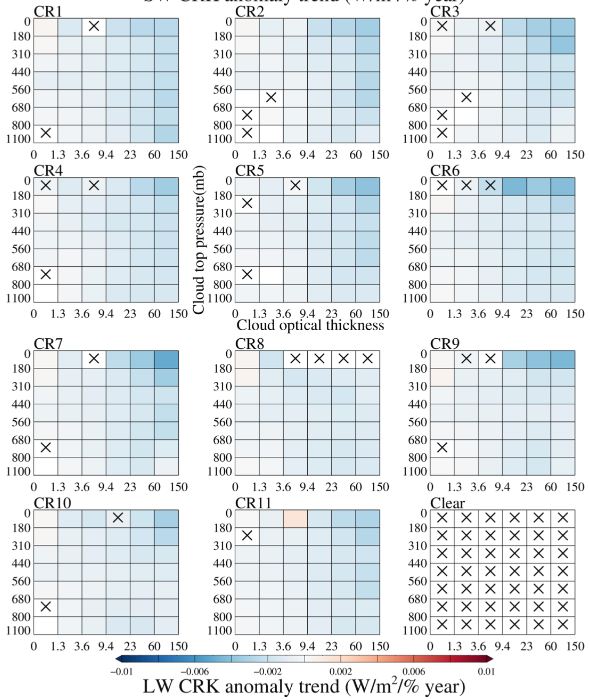






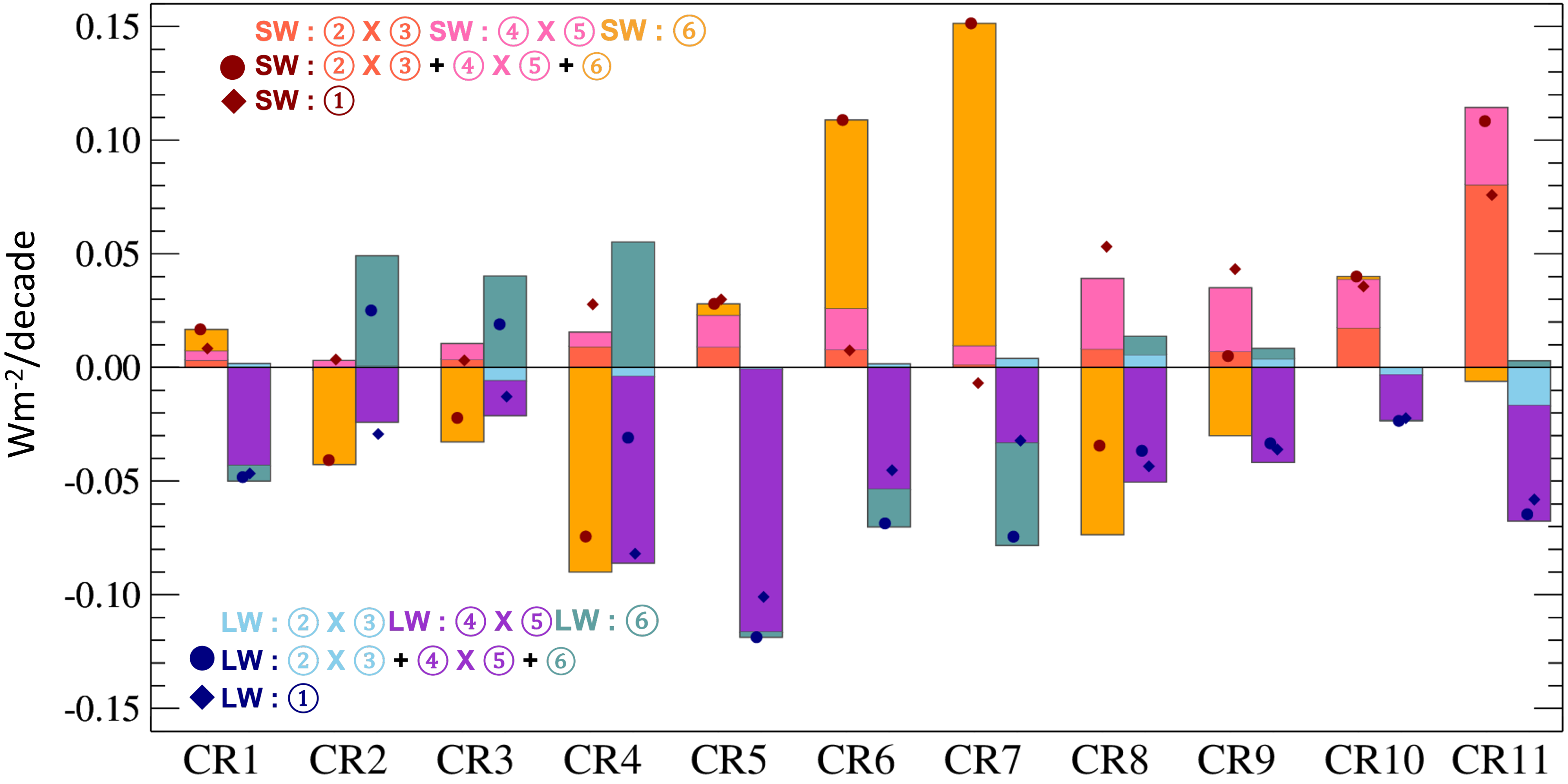






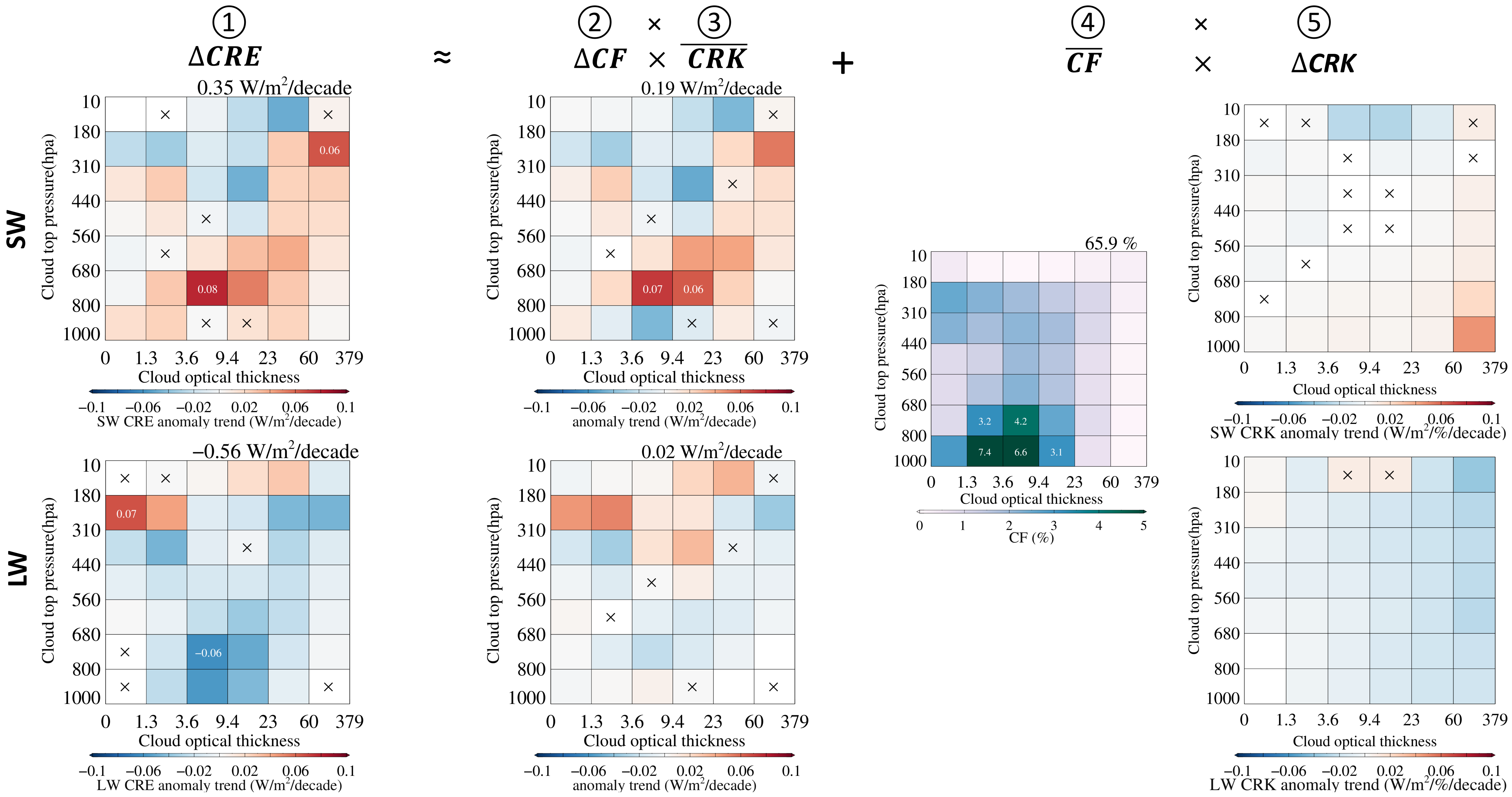
$$\Delta CRE = \underbrace{\sum_{k=0}^{K} \bar{f}_k \Delta C_k \overline{CRK}_k}_{②\times③} + \underbrace{\sum_{k=0}^{K} \bar{f}_k \bar{C}_k \Delta CRK_k}_{④\times⑤} + \underbrace{\sum_{k=0}^{K} \Delta f_k \bar{C}_k \overline{CRK}_k}_{⑥}$$

Daily dataset

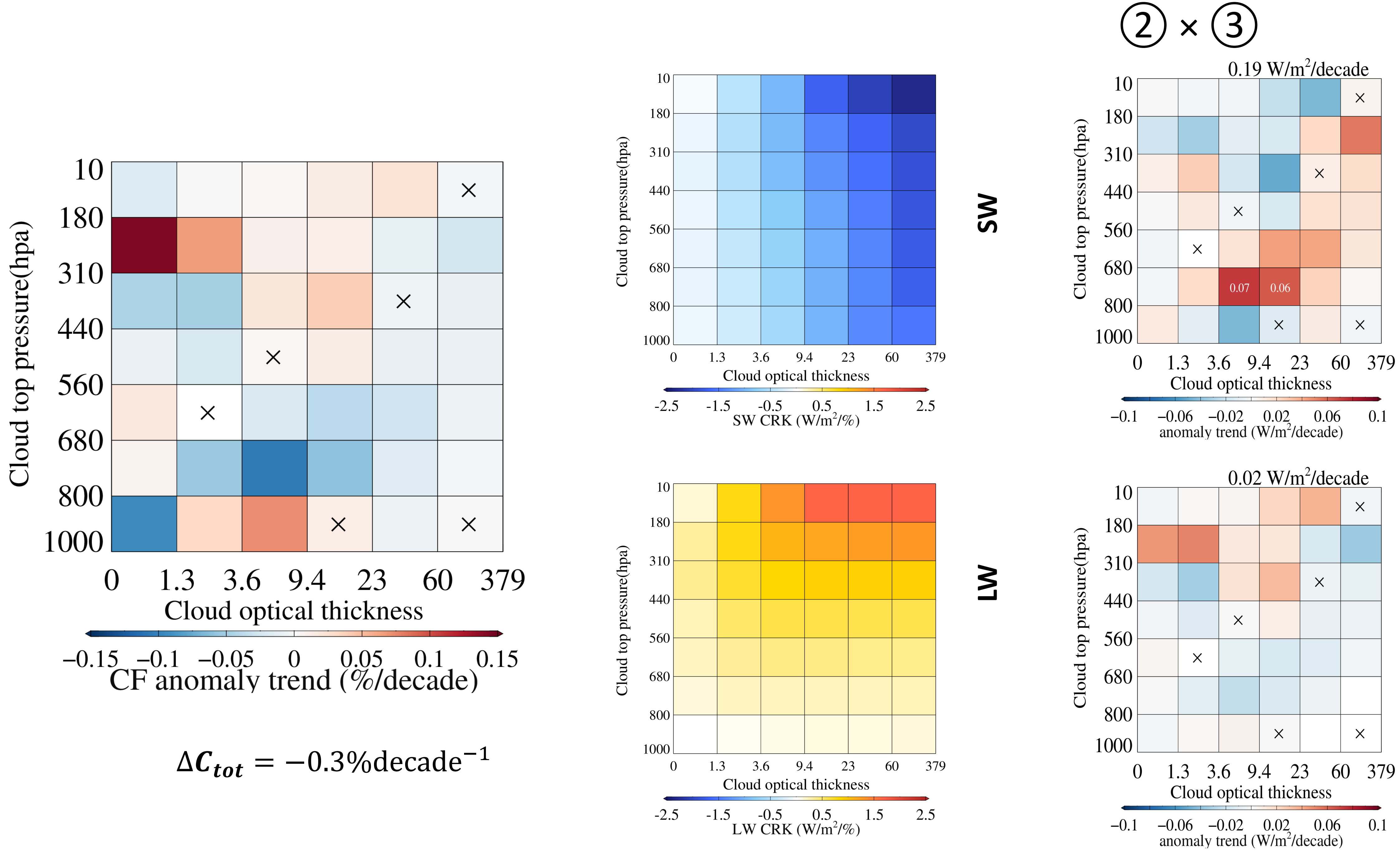


Values from AGU poster

	Daily dataset		Monthly dataset	
	$\Delta CRE \ (= \sum_{k=0}^{K} \Delta CRE_k f_k)$	②×③ + ④×⑤ + ⑥	ΔCRE	②×③ + ④×⑤
SW	0.28	0.29	0.35	0.30
LW	-0.50	-0.45	-0.56	-0.54

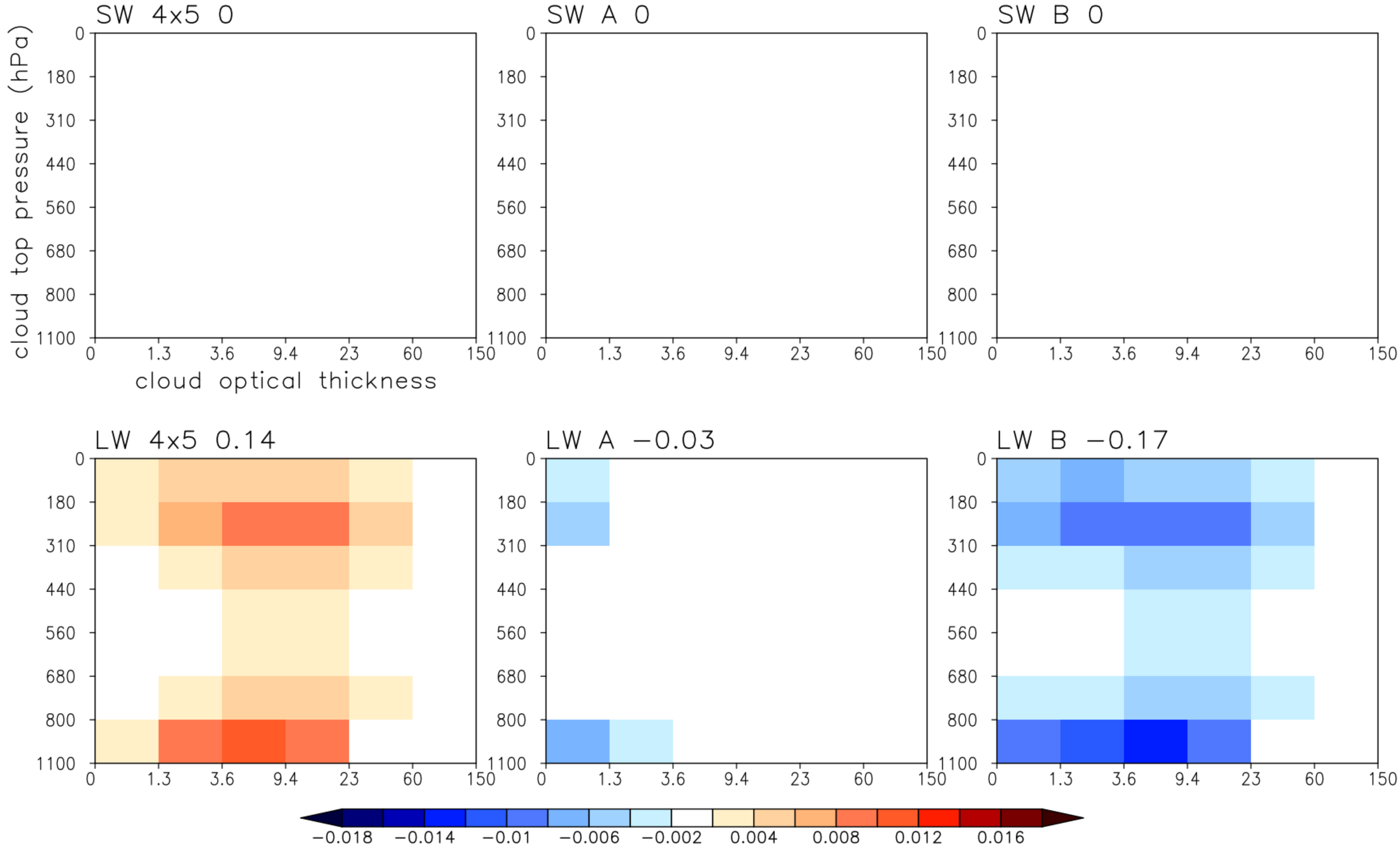


① ΔCRE ≈ ② ΔCF × ③ CRK + ④ CF × ⑤ ΔCRK
SW
LW
0.35 W/m2/decade
0.19 W/m2/decade
65.9 %
−0.56 W/m2/decade
0.02 W/m2/decade
Cloud top pressure(hpa)
Cloud optical thickness
SW CRE anomaly trend (W/m2/decade)
LW CRE anomaly trend (W/m2/decade)
anomaly trend (W/m2/decade)
CF (%)
SW CRK anomaly trend (W/m2/%/decade)
LW CRK anomaly trend (W/m2/%/decade)

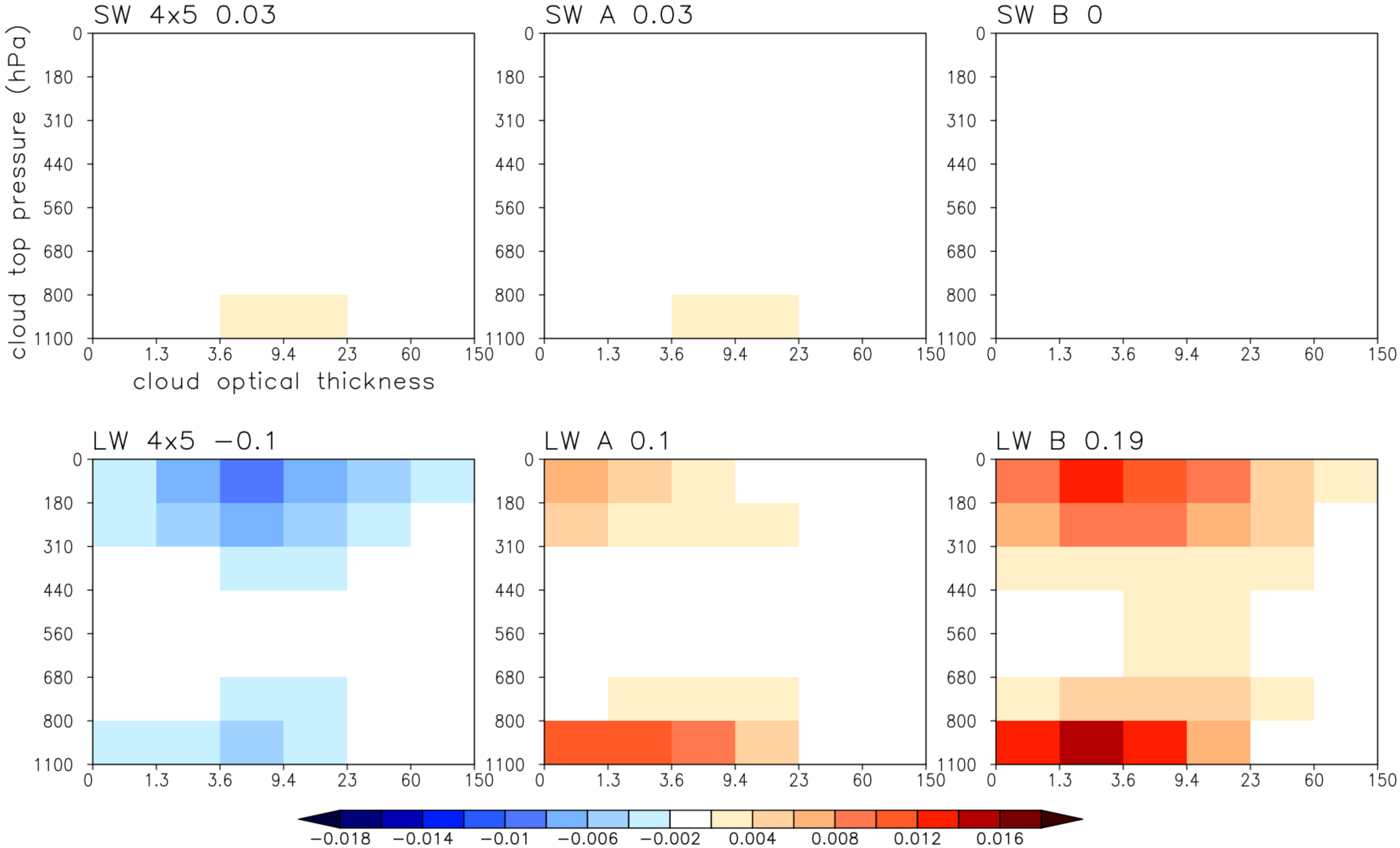


$$\Delta C_{tot} = -0.3\%\text{decade}^{-1}$$

Ts increase


SW 4x5 0
SW A 0
SW B 0
LW 4x5 0.14
LW A −0.03
LW B −0.17
cloud top pressure (hPa)
cloud optical thickness
0
180
310
440
560
680
800
1100
0
1.3
3.6
9.4
23
60
150
−0.018
−0.014
−0.01
−0.006
−0.002
0.004
0.008
0.012
0.016

q increase


SW 4x5 0.03
SW A 0.03
SW B 0
LW 4x5 −0.1
LW A 0.1
LW B 0.19
cloud top pressure (hPa)
cloud optical thickness
0
180
310
440
560
680
800
1100
0
1.3
3.6
9.4
23
60
150
−0.018
−0.014
−0.01
−0.006
−0.002
0.004
0.008
0.012
0.016