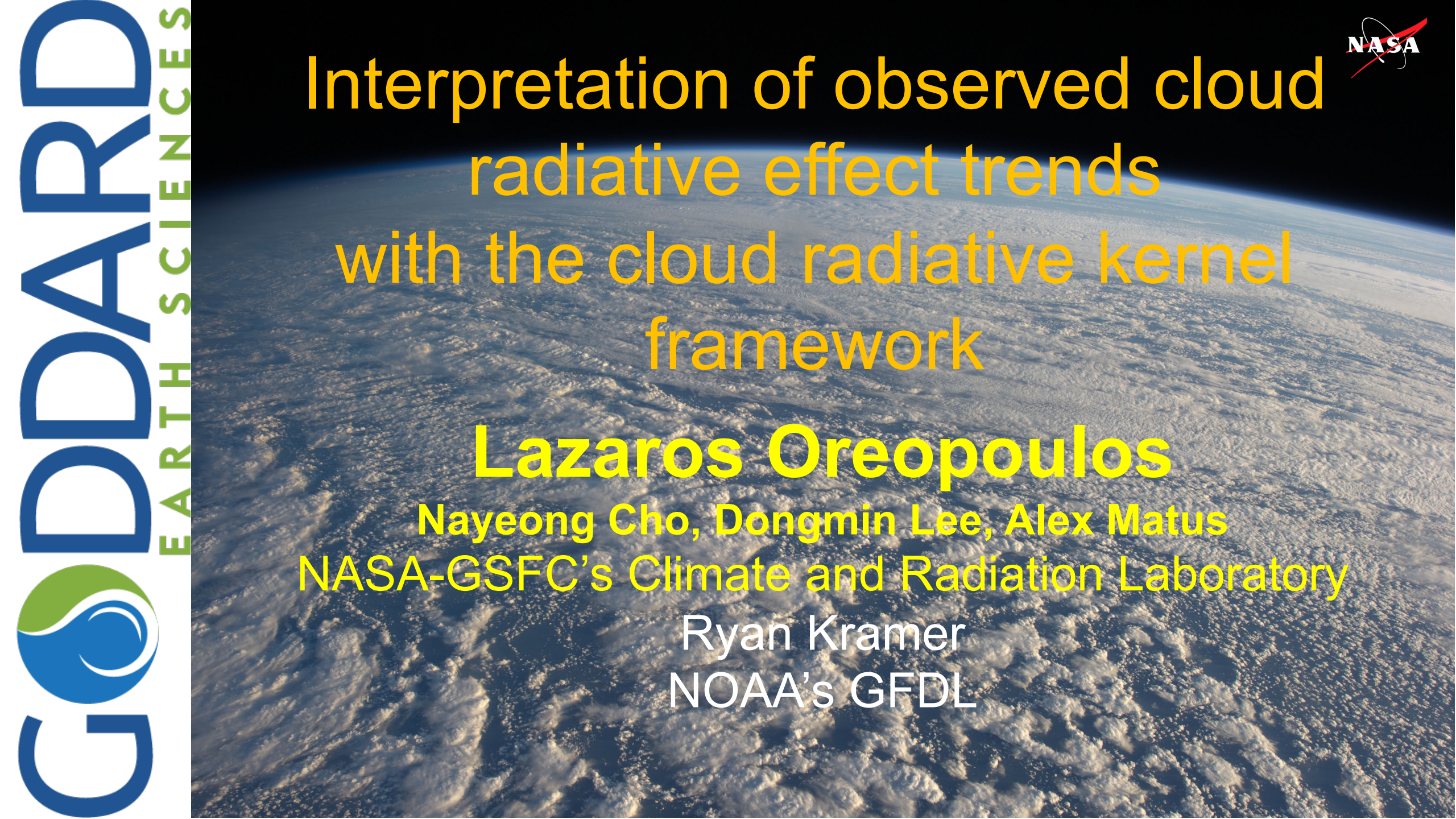

Interpretation of observed cloud radiative effect trends with the cloud radiative kernel framework

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NASA
Background

Cloud Radiative Response (feedback) and CRE

$$CRE = F - F_{clr}$$
$$F = CF_{ovc} + (1 - C)\,F_{clr}$$

overcast CRE

$$CRE = C(F_{ovc} - F_{clr})$$
$$dF = dCRE + dF_{clr}$$

Cloud radiative response (CRR) is $\frac{dF}{dt}$ **only due to cloud changes** or $\frac{dCRE}{dt}$ **only due to cloud changes (**$\frac{dF}{dT_s}$ and $\frac{dCRE}{dT_s}$ for cloud feedback**)**

$$dCRE \approx dC(\overline{F_{ovc}} - \overline{F_{clr}}) + \bar{C}(dF_{ovc} - dF_{clr}) \approx dC(\overline{F_{ovc}} - \overline{F_{clr}}) + \bar{C}\left(dF_{ovc}^{cld} + dF_{ovc}^{mask} - dF_{clr}\right)$$

$$\Longrightarrow dCRE - \bar{C}dF_{ovc}^{mask} + \bar{C}dF_{clr} \equiv dCRE - dCRE^{mask} \approx dC(\overline{F_{ovc}} - \overline{F_{clr}}) + \bar{C}dF_{ovc}^{cld}$$

Adjusted CRE anomaly method

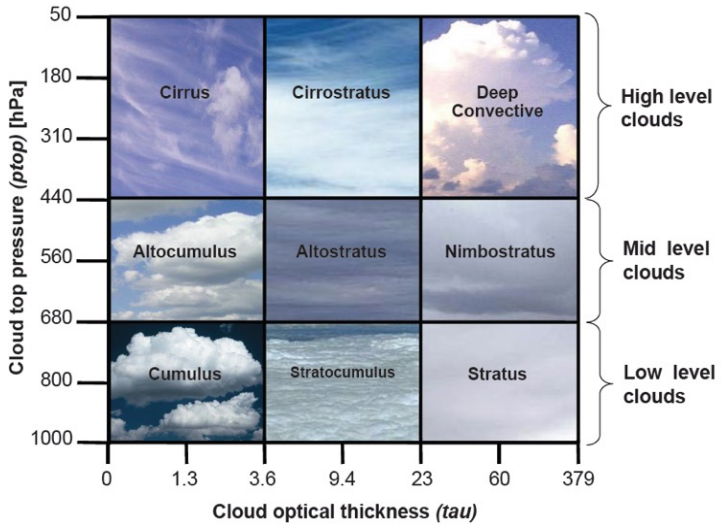
Cloud Radiative Kernel (CRK) method

Can use $dCRE$ only after having removed both dF_{clr} AND non-cloud effects on dF_{ovc}, i.e., after adjustment for *"cloud masking"* effects. Or we can use the RHS (red) in a fixed environment assuming $dF_{ovc}^{cld} \approx 0$, i.e., staying within a specific cloud type (narrow range of cloud properties)

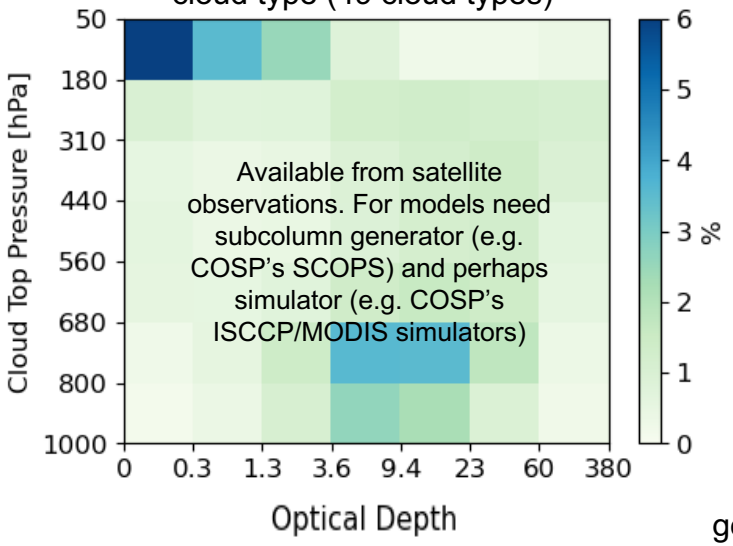
Cloud Radiative Kernels

Schematic: Swati Gehlot

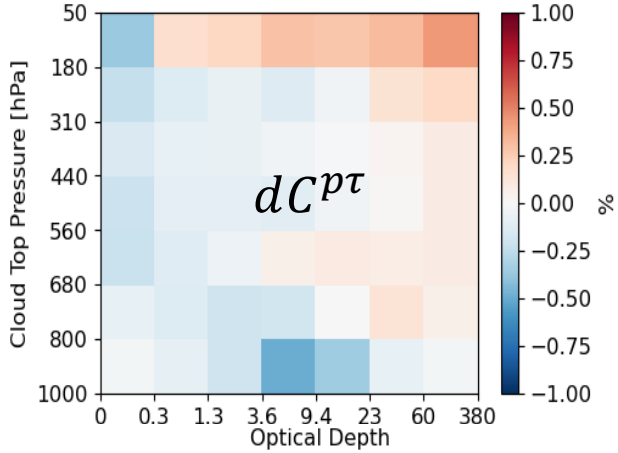
F_{ovc} depends on cloud type for a fixed environment



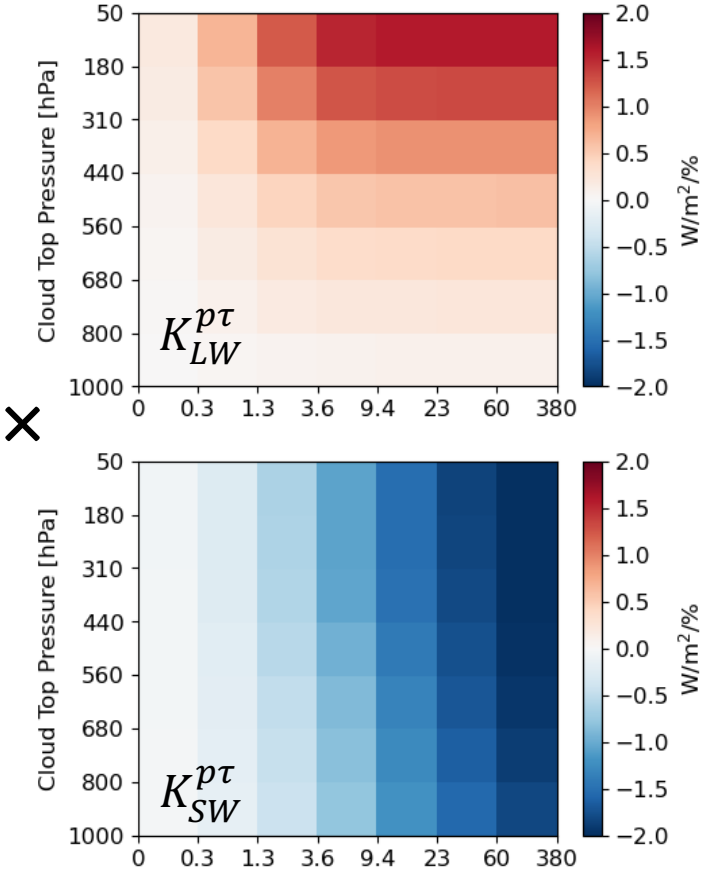
More detailed cloud amount distribution by cloud type (49 cloud types)



Courtesy of Mark Zelinka



Can be precalculated (fixed), resolved by month, latitude (e.g., Zhou et al. 2013)



$\approx dF^{p\tau}$

available from CERES Flux By Cloud Type product (FBCT)

$$CRR_K^{p\tau}(\theta,\phi) = \frac{\overline{K^{p\tau}(m,\theta,\phi)} \times dC^{p\tau}(y,m,\theta,\phi)}{dt}$$

available from FBCT, MODIS/VIIRS COSP

geographically resolved feedback $y = year, m = month$

$$K_{SW,LW}^{p\tau} = \frac{(F_{ovc} - F_{clr})_{SW,LW}}{100}$$

Cloud Radiative Response from adjusted CRE

$$dF = IRF + \overbrace{radiative\ response}^{ERR + CRR}$$

includes fast and slow RR

$$dF = \underbrace{ERF}_{\text{IRF + fast RR}} + \underbrace{radiative\ response}_{\text{only slow RR}}$$

$$dF = dCRE + dF_{clr} = dCRE + IRF_{clr} + ERR_{clr}$$
$$dF = IRF + ERR + CRR$$
$$\Big\} \; CRR = dCRE - (ERR - ERR_{clr}) - (IRF - IRF_{clr})$$

$$CRR_{adj} \equiv dCRE_{adj} = dCRE - ERR^{mask} - IRF^{mask}$$

$$ERR^{mask} = \left(K^T - K^T_{clr}\right)dT + \left(K^q - K^q_{clr}\right)dq + (K^\alpha - K^\alpha_{clr})d\alpha$$ (K^X are radiative kernels)

$$IRF^{mask} = IRF - IRF_{clr}$$

$$IRF_{clr} = dF_{clr} - ERR_{clr} = dF_{clr} - K^T_{clr}\,dT - K^q_{clr}\,dq - K^\alpha_{clr}\,d\alpha$$

$$IRF = dF - ERR - CRR = dF - K^T dT - K^q dq - K^\alpha d\alpha - CRR$$

$$IRF = \frac{IRF_{clr}}{constant}$$

Application to CERES

Lazaros Oreopoulos, Nayeong Cho, Ryan Kramer, Dongmin Lee and Alex Matus. Cloud Radiative Effect Variability in the Recent Satellite Record and Associated Cloud Feedback. *ESS Open Archive* . February 13, 2026. DOI: 10.22541/essoar.177100425.52102553/v1
Under review for J. Climate

Satellite and other datasets

- CERES Flux by Cloud Type (FBCT) **2002.7-2023.2**
  - Provides $C^{p\tau}$, F_{clr}, $F_{ovc}^{p\tau}$, and thus $K^{p\tau}$ resolved by year (y), month (m), lat (θ), lon (ϕ), at 1°
- Precalculated (fixed) $K^{p\tau}$ resolved by month, lat (Zhou et al. 2013), resampled at 1°

$$CRR_K^{p\tau}(\theta,\phi) = \frac{\overline{K^{p\tau}(m,\theta,\phi)} \times dC^{p\tau}(y,m,\theta,\phi)}{dt} \quad (\mathrm{Wm^{-2}decade^{-1}})$$

- Temperature and WV profiles from CLIMCAPS; broadband surface albedo from CERES EBAF

$$CRR_{adj}(\theta,\phi) = \frac{dCRE_{adj}(\theta,\phi,m,y)}{dt} \quad (\mathrm{Wm^{-2}decade^{-1}})$$

Simplified notation not showing dependences:

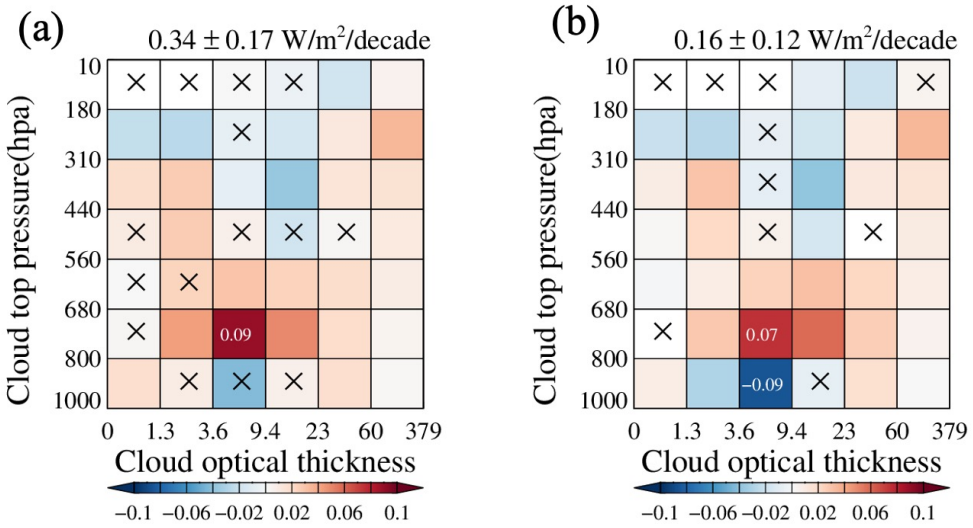
$$CRR_K = \overline{K} \times dC$$

$$CRR_{adj} = dCRE_{adj}$$

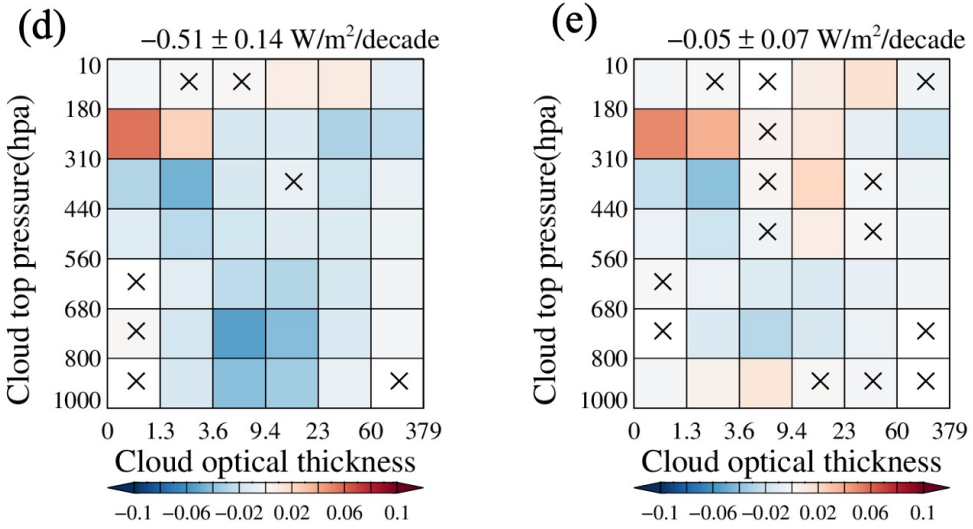
2002.7 – 2023.2

directly calculated $dCRE$ ≠ cloud anomaly (CRR) $dC \times \bar{K}$

SW



LW



Red= warming: less SW reflectance, less LW emission
Blue=cooling: more SW reflectance, more LW emission

It can be easily shown that (simplified notation):

$$dCRE = \underbrace{d\bar{C} \times \bar{K}}_{\text{CRR}} + \underbrace{\bar{C} \times dK}_{\text{kernel anomaly}} + covariance$$

(we have kind of seen this before)

$$dC(\overline{F_{ovc}} - \overline{F_{clr}}) + \bar{C}(dF_{ovc} - dF_{clr})$$

$$CRE = \overline{CRE} + dCRE$$

$$\boldsymbol{C} = \bar{\boldsymbol{C}} + d\boldsymbol{C}$$

$$\boldsymbol{K} = \bar{\boldsymbol{K}} + d\boldsymbol{K}$$

$$CRE = \boldsymbol{C}\times\boldsymbol{K} = (\bar{\boldsymbol{C}} + d\boldsymbol{C})\times(\bar{\boldsymbol{K}} + d\boldsymbol{K})$$

$$= \underbrace{\bar{\boldsymbol{C}}\times\bar{\boldsymbol{K}}}_{\overline{CRE}} + \underbrace{\bar{\boldsymbol{K}}\times d\boldsymbol{C} + \bar{\boldsymbol{C}}\times d\boldsymbol{K} + d\boldsymbol{C}\times d\boldsymbol{K}}_{dCRE}$$

directly calculated

from cloud anomaly + kernel anomaly (no covariance)

cloud anomaly term (CRR)

kernel anomaly term

$$dCRE \approx dC \times \overline{K} + \overline{C} \times dK$$

SW

(a) 0.34 ± 0.17 W/m²/decade

agreement

0.34 W/m²/decade

(b) $dC \times \overline{K}$ 0.16 ± 0.12 W/m²/decade

(c) $\overline{C} \times dK$ 0.17 ± 0.14 W/m²/decade

LW

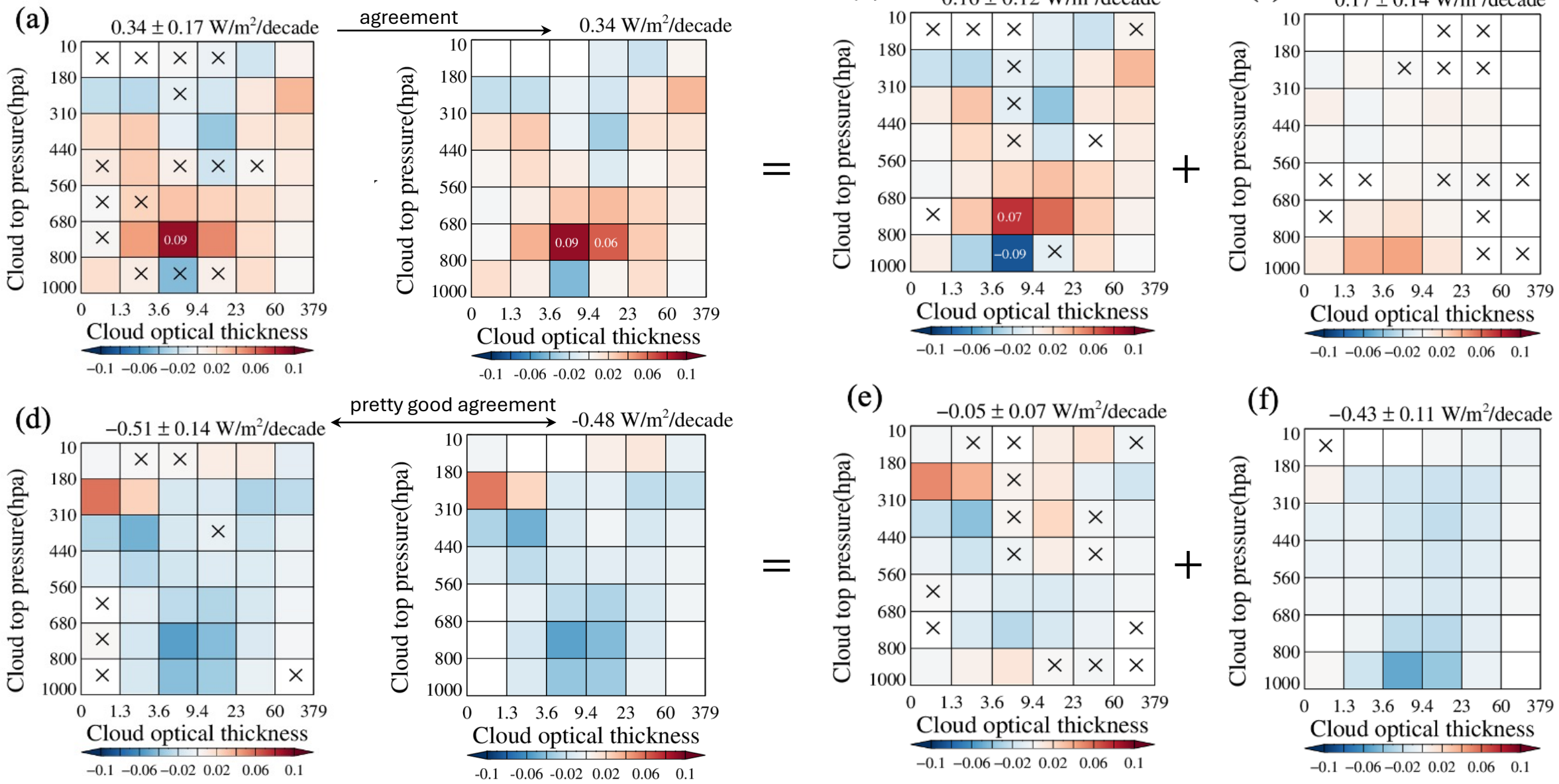
(d) −0.51 ± 0.14 W/m²/decade

pretty good agreement

-0.48 W/m²/decade

(e) −0.05 ± 0.07 W/m²/decade

(f) −0.43 ± 0.11 W/m²/decade

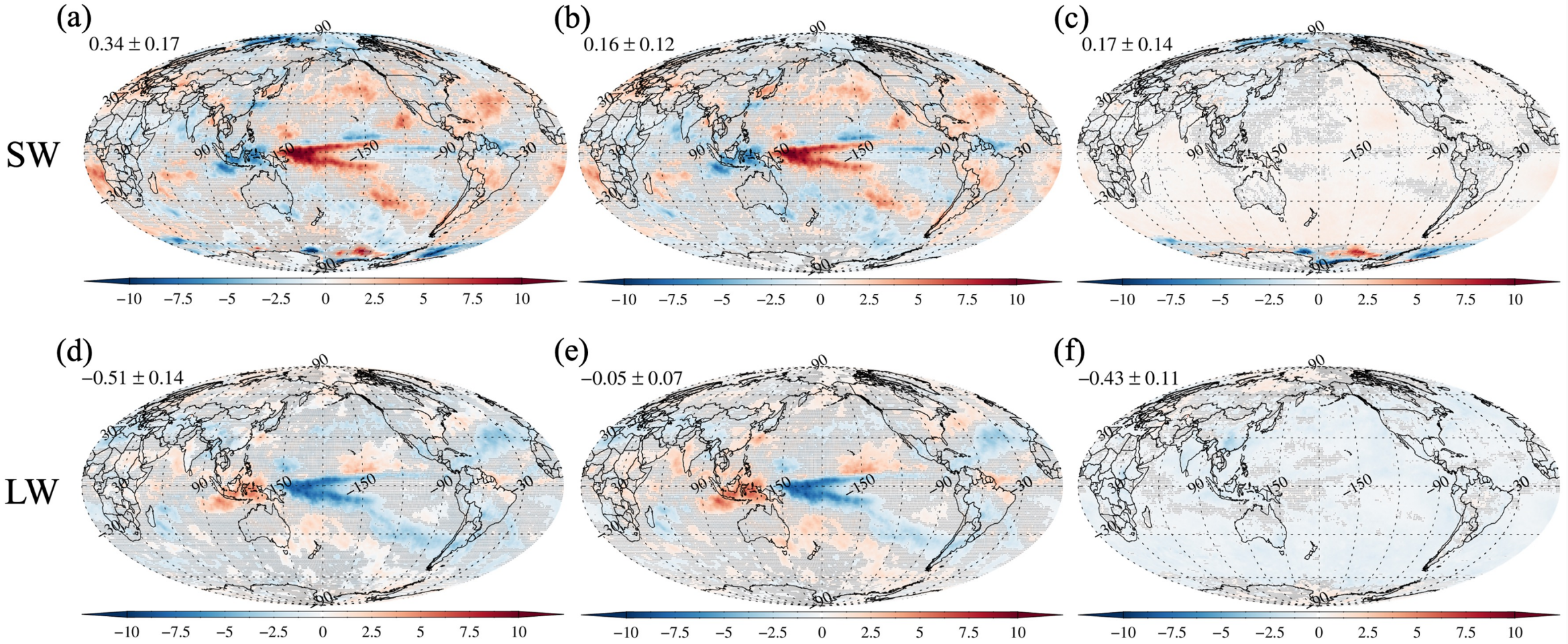


Red= warming: less SW reflectance, less LW emission

Blue=cooling: more SW reflectance, more LW emission

Geographical distribution

$dCRE$ | $d\mathbf{C} \times \bar{\mathbf{K}}$ | $\bar{\mathbf{C}} \times d\mathbf{K}$



Red= warming: less SW reflectance, less LW emission

Blue=cooling: more SW reflectance, more LW emission

Big picture of everything

$$dCRE \approx dC \times \overline{K} + \overline{C} \times dK$$

$$dCRE \approx dC \times \overline{(F_{ovc} - F_{clr})} + \overline{C} \times dF_{ovc} - \overline{C} \times dF_{clr}$$

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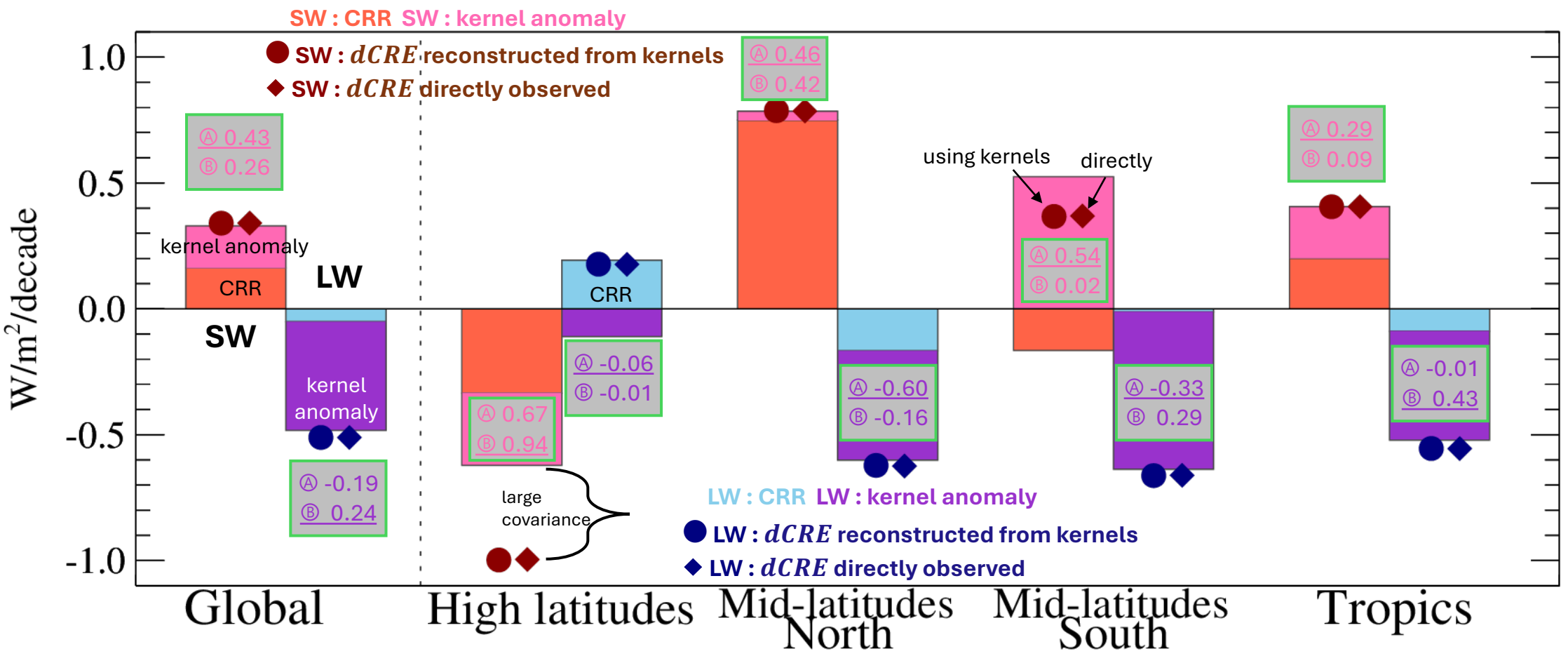
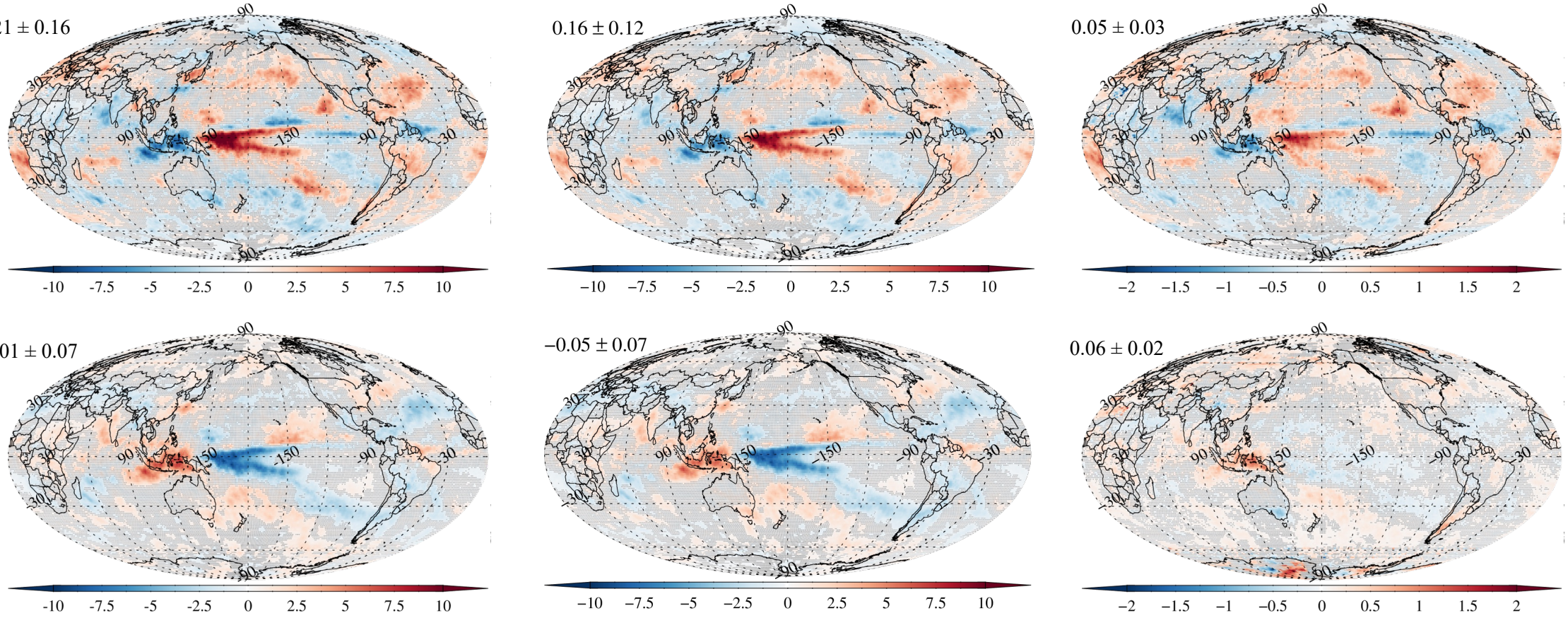


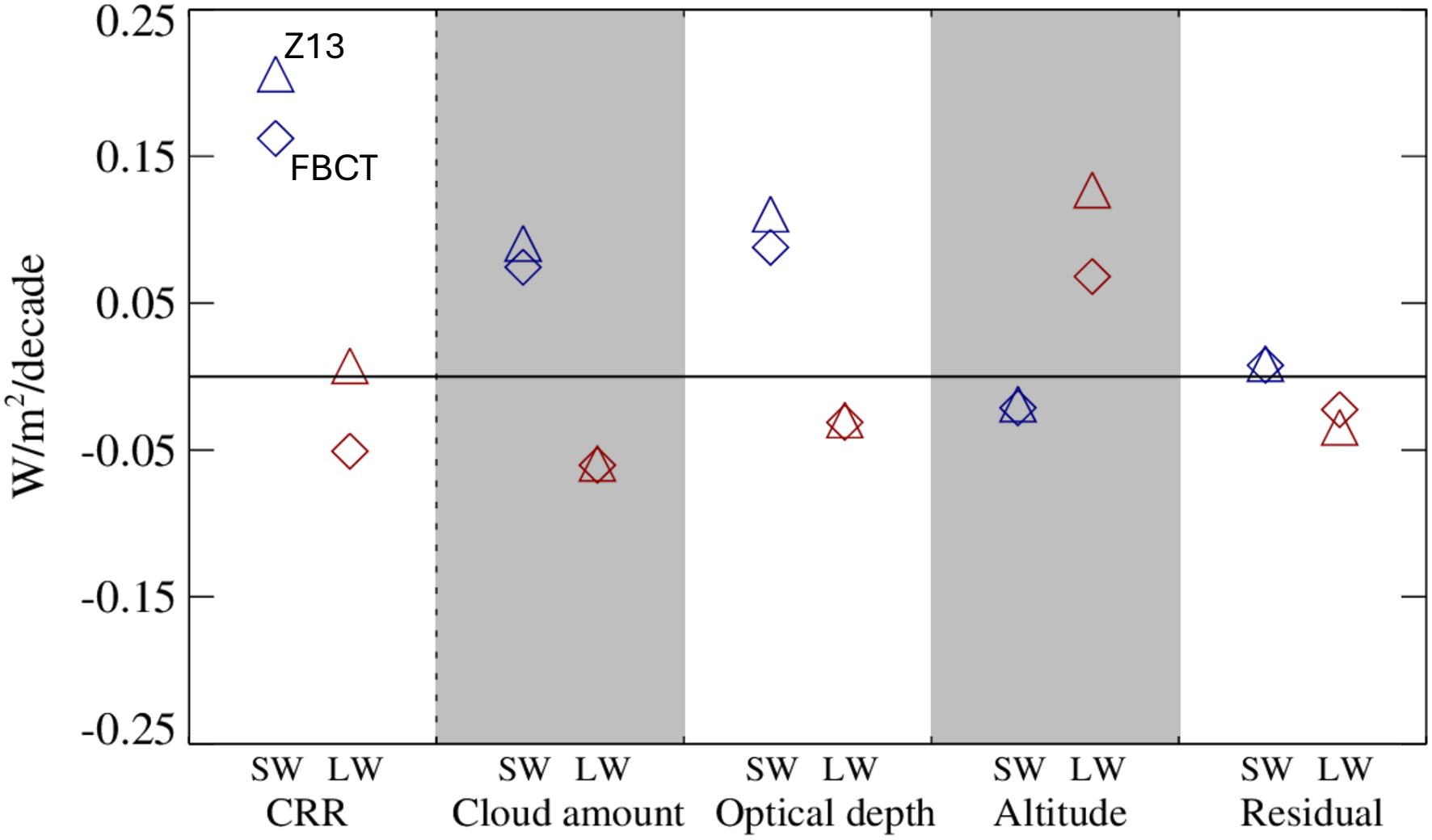
(30° and 60° lat are used to define the domains, not area-weighted)

Impact of Cloud Radiative Kernel differences on CRR

	Pre-calculated Z13	FBCT	Difference $dC \times (K_{Z13} - \bar{K})$
SW	0.21 ± 0.16	0.16 ± 0.12	0.05 ± 0.03
LW	0.01 ± 0.07	−0.05 ± 0.07	0.06 ± 0.02



CRR decomposition



$$CRR = CRR^{C} + CRR^{\tau} + CRR^{p} + CRR^{res}$$

Methodology : Zelinka et al., 2013

Comparison between CRRs from CRK and adjusted CRE

$$CRR_{adj} = dCRE - ERR^{mask} - IRF^{mask}$$

$$CRR_K = \bar{\boldsymbol{K}} \times d\boldsymbol{C} \approx dCRE - \bar{\boldsymbol{C}} \times d\boldsymbol{K} - d\boldsymbol{C} \times d\boldsymbol{K} =$$

$$= dCRE - \bar{C}\left(dF_{ovc}^{cld} + dF_{ovc}^{mask} - dF_{clr}\right) - d\boldsymbol{C} \times d\boldsymbol{K} = dCRE - dCRE^{mask} - \bar{C}dF_{ovc}^{cld} - d\boldsymbol{C} \times d\boldsymbol{K}$$

Even if $ERR^{mask} + IRF^{mask} \approx dCRE^{mask}$ the CRK-based adjusted CRE subtracts the additional term

$$\bar{C}dF_{ovc}^{cld} + d\boldsymbol{C} \times d\boldsymbol{K}$$

For pre-calculated/fixed cloud radiative kernels there are no masking effects to remove!

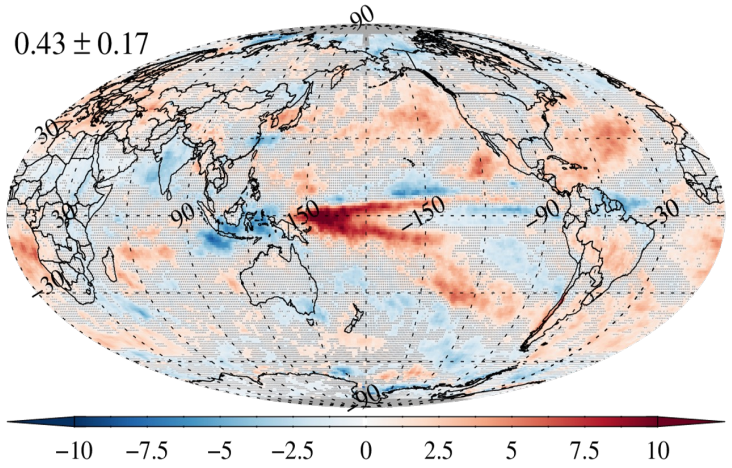
Adjusted CRE vs CRK-based CRR

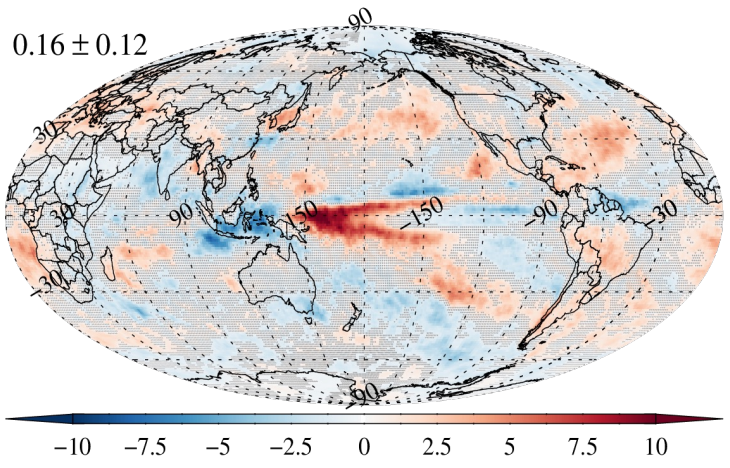
Adjusted CRE

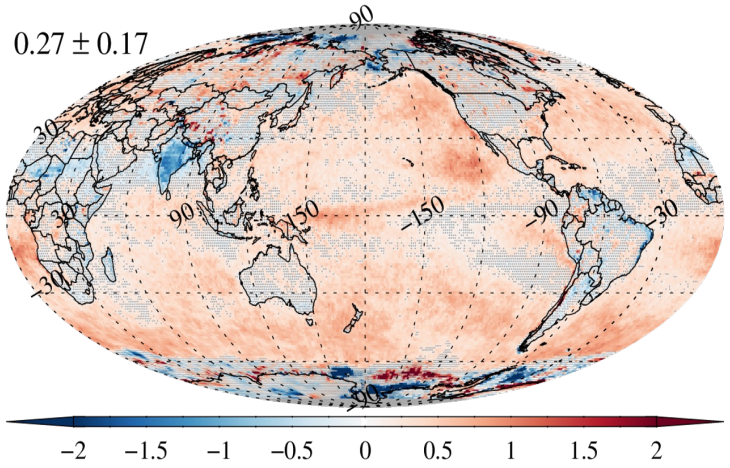
CRK-based ($dC \times \bar{K}$)

difference

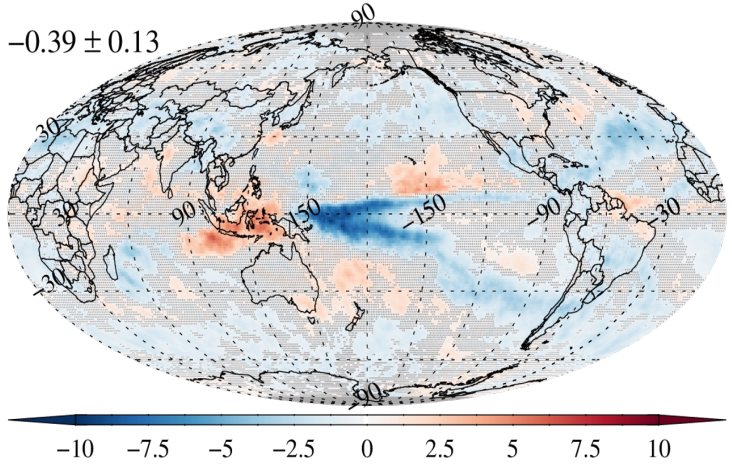
SW

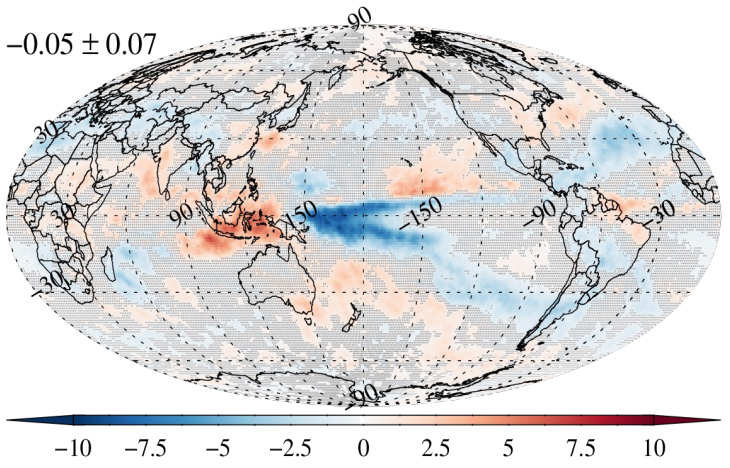


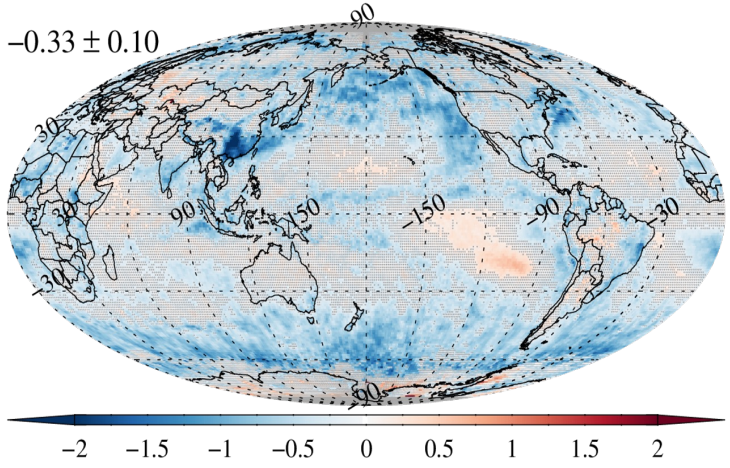




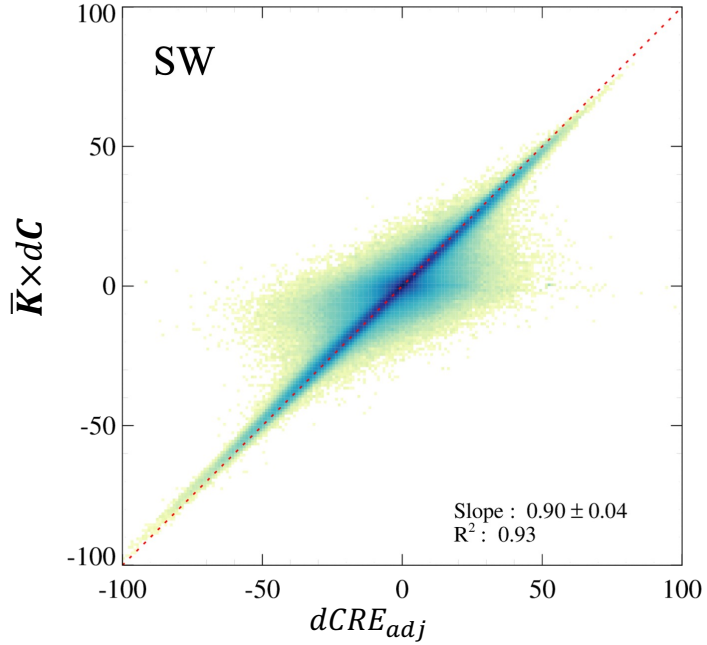
LW

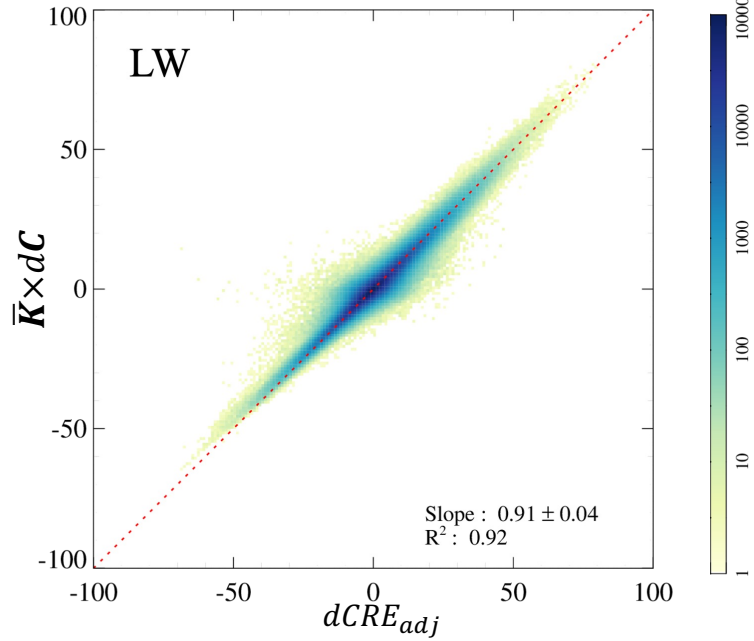


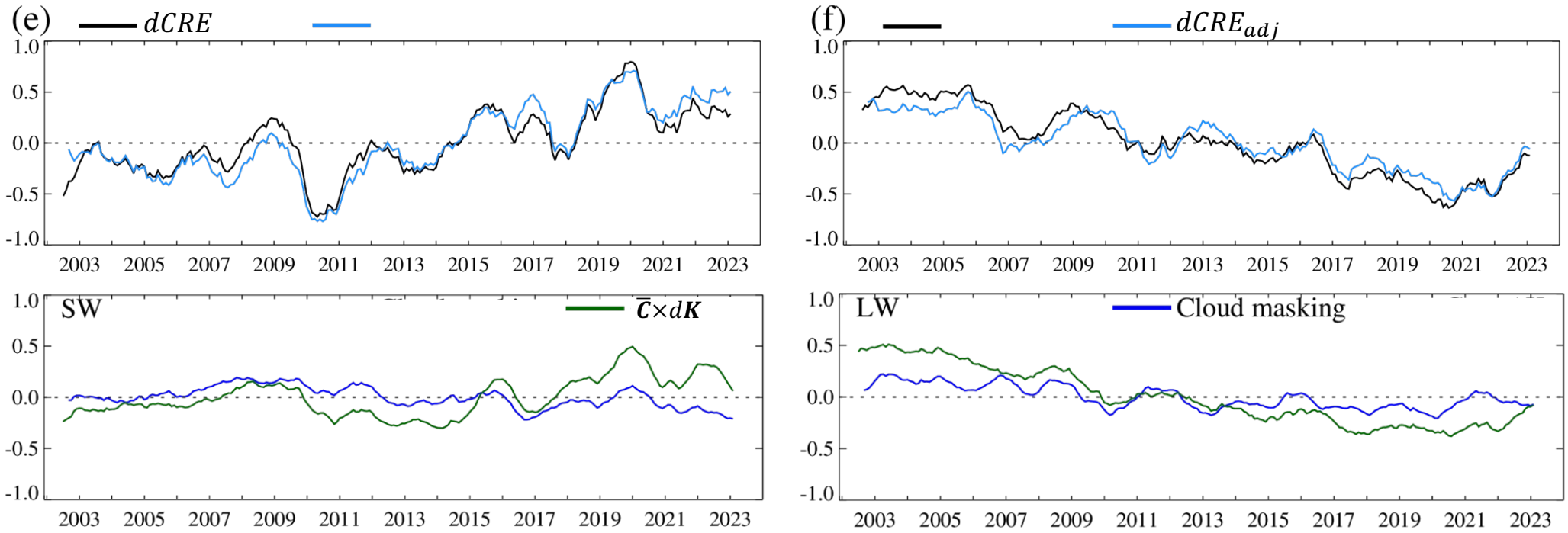




Closer look at adjusted CRE vs CRK anomalies







Summary

- Real world (FBCT) cloud radiative kernels are variable, so not obvious how to calculate cloud radiative response (CRR) from observations (means can be used)
  - Kernel variability may be due to both cloud (internal changes within cloud types) and non-cloud changes
  - The cloud radiative effect (CRE) trend can be recovered by combining the cloud radiative response term (from multi-annual kernel means) and kernel anomaly terms
- For a recent 20+ year period, local magnitudes of CRR are much larger than those of kernel anomaly but this ceases to be true at global scales because of extensive cancellations
  - $0 < CRR_K^{SW} < dCRE^{SW} < CRR_{adj}^{SW}$
  - $0 \approx \left|CRR_K^{LW}\right| < |dCRE^{LW}| > \left|CRR_{adj}^{LW}\right|$ (all values are negative)
  - $\left|CRR_K^{LW}\right| \approx 0$ partly due to opposing contributions from cloud fraction and altitude anomalies
- The CRR from cloud the radiative kernel and adjusted CRE (anomaly) methods differ to first order by $\bar{C}dF_{ovc}^{cld} + d\boldsymbol{C}\times d\boldsymbol{K}$

Unaccounted cloud feedback in the CRK framework ($\bar{C}dF_{ovc}^{cld}$)?