Impact and Variability of Cloud Types on Earth's Top-of-Atmosphere Energy Balance in the Tropics

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Motivations, objective and data set

Motivations:

1) Convection is generally more intense over land than over the ocean;
2) Land-based convection typically features wider cores that are more shielded from entrainment than their oceanic counterparts;
3) How do these differences in convective intensity and entrainment influence the cloud radiative effects (CREs) across all cloud types?

Objective:

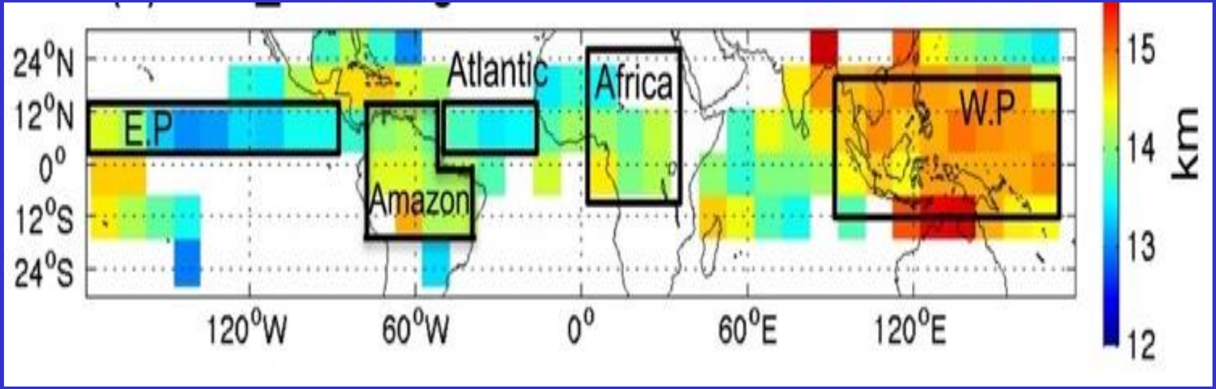
To characterize the impact and variability of cloud types on CREs across convectively active tropical regions, relative to the tropical mean (25°S-25°N)

Data set:

19-yrs high-resolution (2x2 km^2) CERES FBCT (flux by cloud type; Sun *et al.*, 2022) data, similar to the ISCCP data but adding cloud-type-mean cloud properties and radiative fluxes

Sun, M., *et al.*, (2022). Clouds and the Earth's Radiant Energy System (CERES) FluxByCldTyp Edition 4 data product. *J. Atmos. Oceanic Tech.*, 39, 303–318.

Where are the tropical “chimney” zones? (Takahashi *et al.*, 2017)



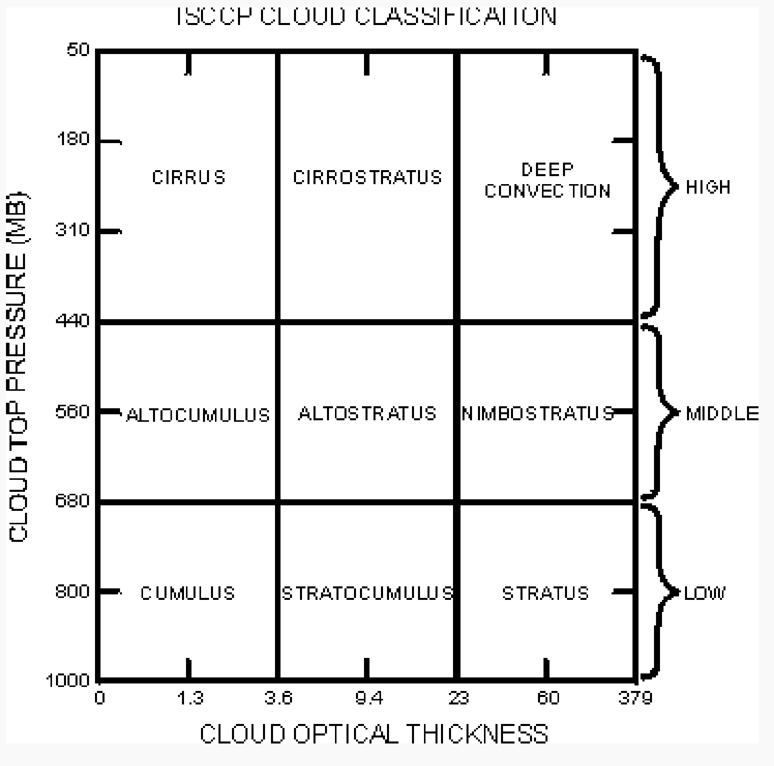
The entire tropics: 25°S-25°N

Tropical ”Chimney” zones:

Lands: Equatorial Africa and Amazonia

Ocean: Eastern Pacific ITCZ, Atlantic ITCZ, and the Tropical Western Pacific

The ISCCP cloud classification (Rossow & Schiffer, 1999)

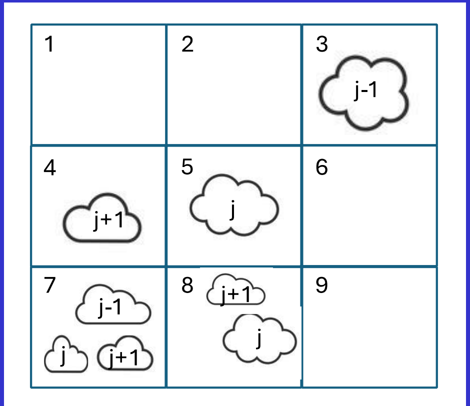


42 cloud types are based upon joint cloud top pressure (p_c; 7 bins) and cloud optical depth (τ; 6 bins) distributions

Cloud-type-mean CREs and decomposition of regional CRE differences

Cloud-type-mean CRE: CRE = F_{clear} - F_{cloudy}

- Regional-mean clear-sky flux is calculated using only the 1°x1° grid cells where the specific cloud type is present (see Xu *et al.*, 2024; JGR)



Differences in cloud-type-mean CREs between a specific region and the tropical mean (designed as region 0 in this study)

$$f_1 CRE_1 - f_0 CRE_0 = (f_0 + \Delta f) \times (CRE_0 + \Delta CRE) - f_0 \times CRE_0$$
$$= f_0 \Delta CRE + \Delta f\, CRE_0 + \Delta f\, \Delta CRE$$

$f_0 \Delta CRE$: the CRE deviation component,

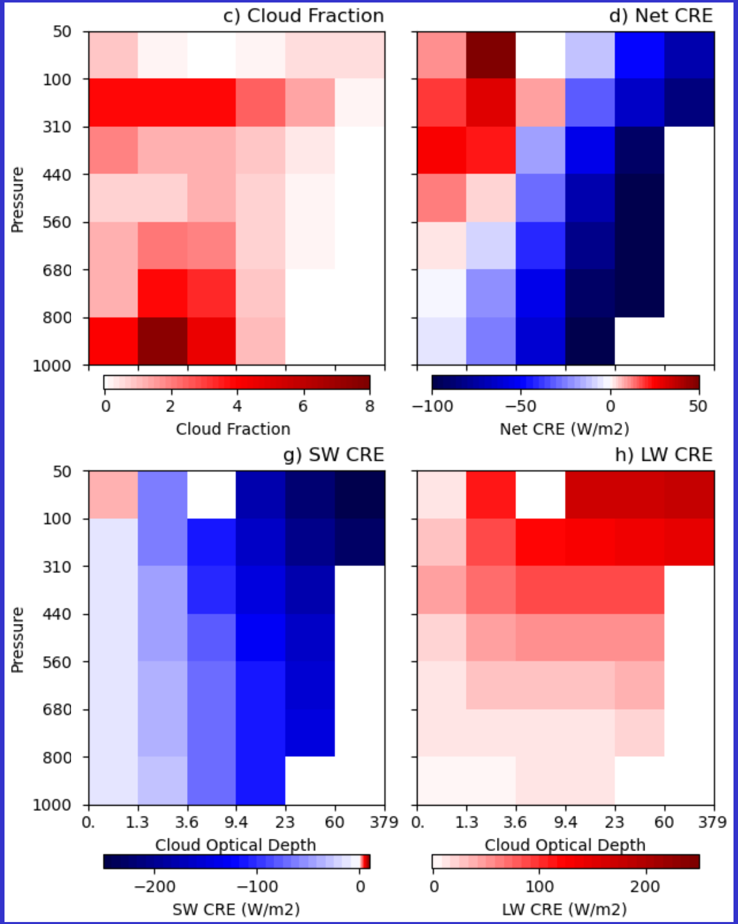
$\Delta f\, CRE_0$: the cloud fraction (CF) deviation component,

$\Delta f\, \Delta CRE$: the nonlinear interaction term.

The total CRE difference is the sum of these components across all cloud types

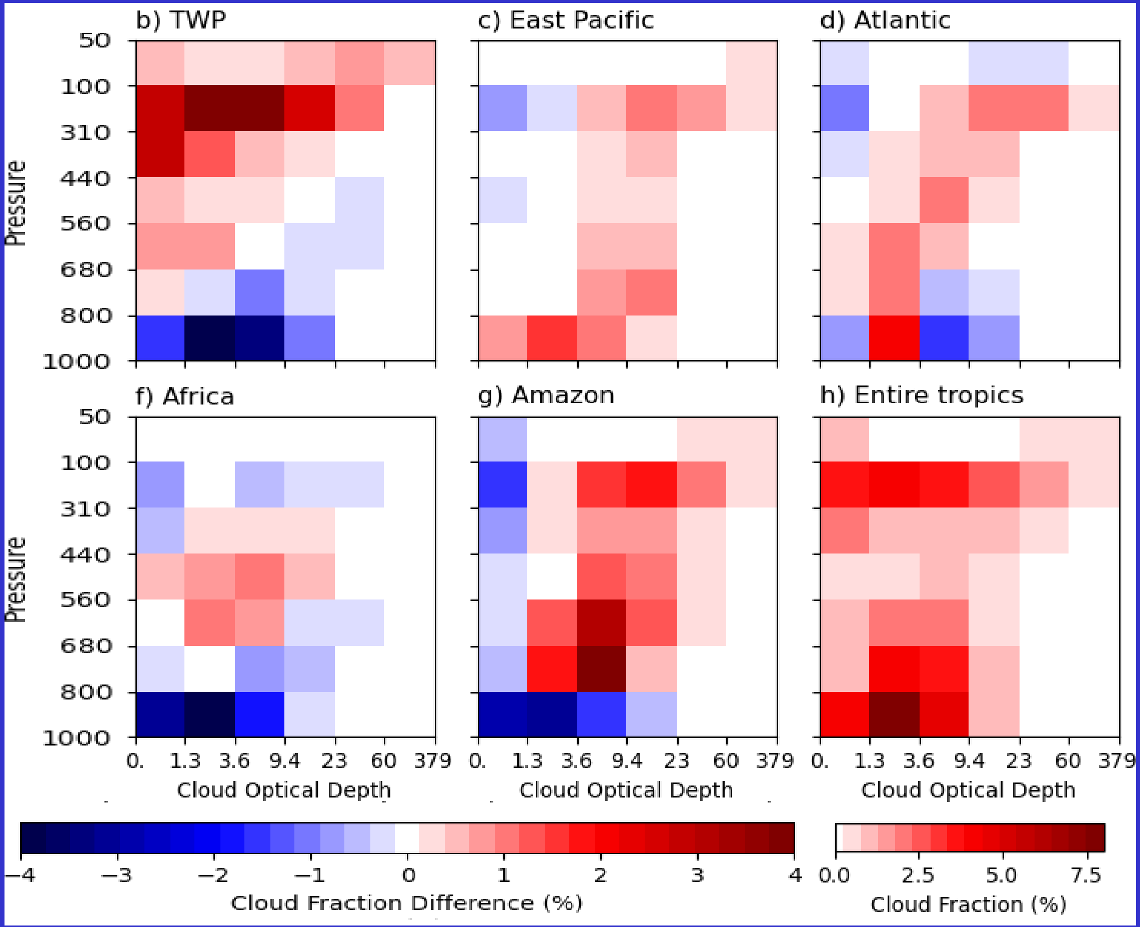
$\Delta CRE_{total} = \sum_{j=1}^{42} f_{0,j} \Delta CRE_j + \sum_{j=1}^{42} \Delta f_j CRE_{0,j} + \sum_{j=1}^{42} \Delta f_j\, \Delta CRE_j$

Tropical-mean cloud fractions and radiative effects (CREs)



- Maximum cloud fractions (%) occur in the lower and upper troposphere (panel c)
- SW, LW and net CREs show strong dependence on cloud optical depth (panels d, g, and h)
- SW, LW and net CREs also vary significantly with cloud top pressure
- Cloud types with lower tops and higher optical depths generally produce net cooling effects (panel d)

Cloud fraction differences from the tropical mean among the five regions



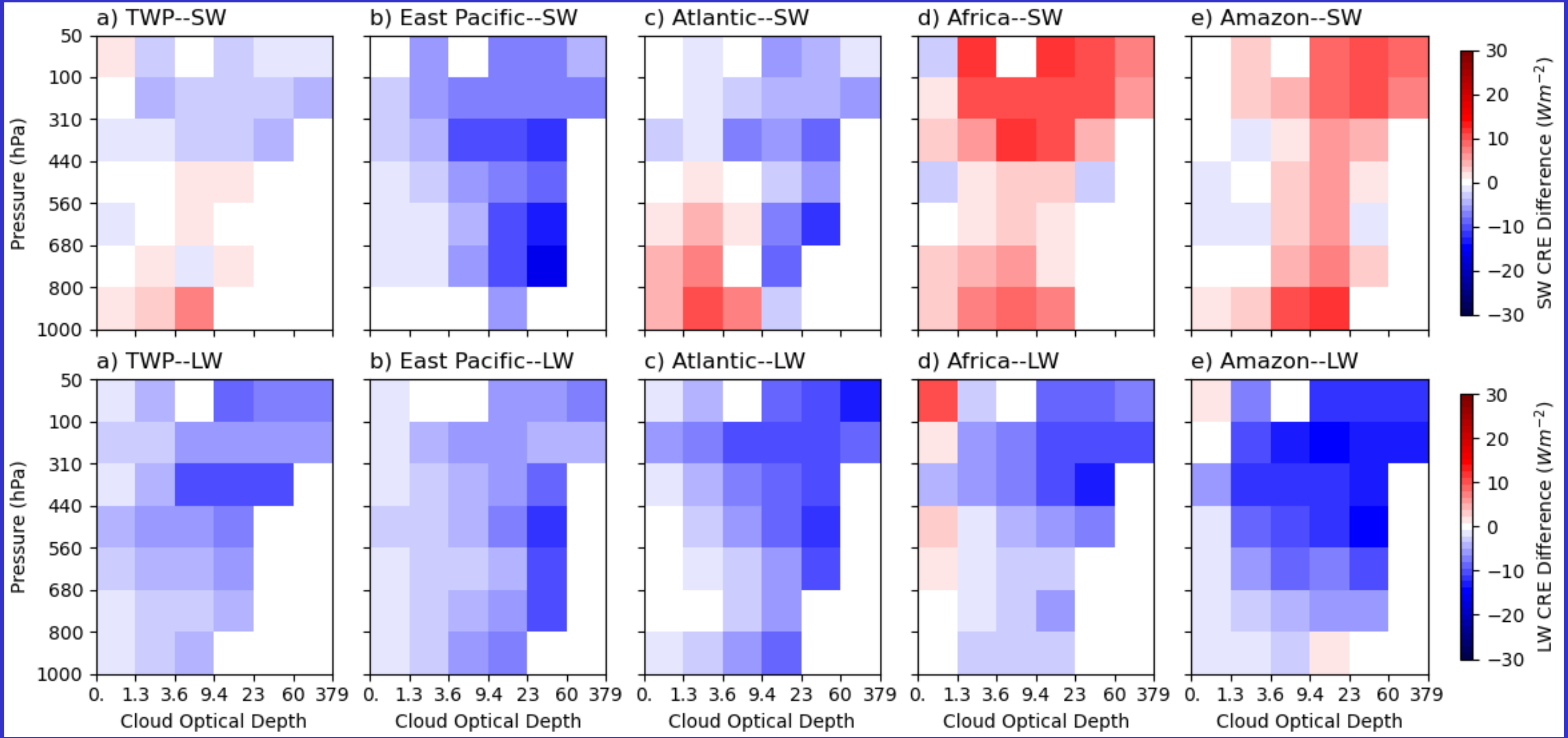
1) The five "chimney" regions (b, c, d, f, g) are cloudier than the tropical mean (h), except for some low/boundary-layer cloud types in four of them

2) Boundary-layer clouds are generally less abundant than the tropical mean, except in the Eastern Pacific & one type in Atlantic.

3) The Tropical Western Pacific (TWP) exhibits the highest fraction of anvil cloud types; while Africa shows the lowest

4) The Amazon region has the smallest fraction of optically thin cloud types

SW (top row) and LW (bottom row) CRE differences from the tropical mean

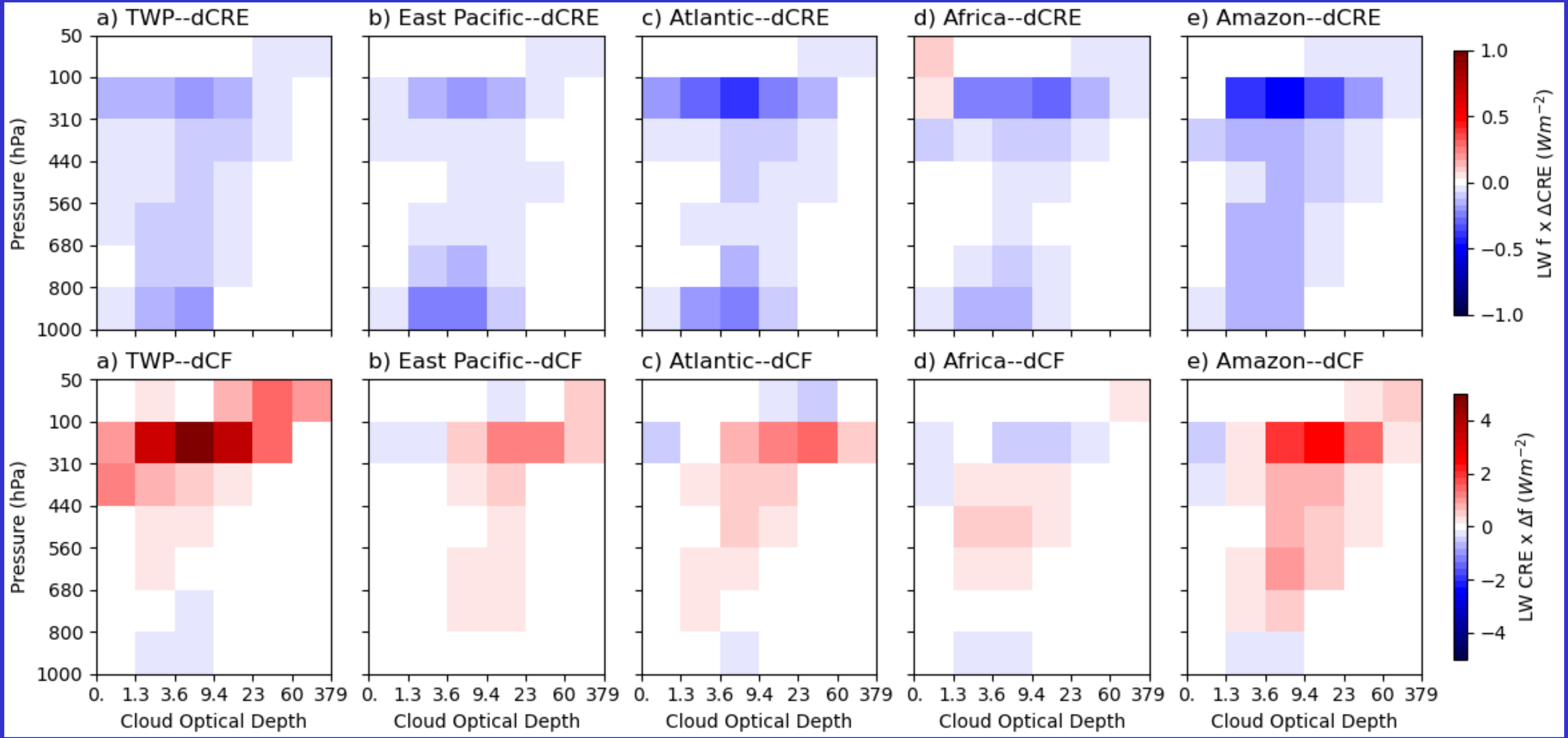


1) SW CRE: stronger cooling over oceans but weaker cooling over land, related to cloud water content differences
2) LW CRE: reduced warming across nearly all cloud types, linked to more humid environments outside of clouds in these convectively active regions

LW CRE decomposition: CRE deviation (top row) and CF deviation (bottom)

$f_{0,j}\ \Delta CRE_j$

$CRE_{0,j}\ \Delta f_j$

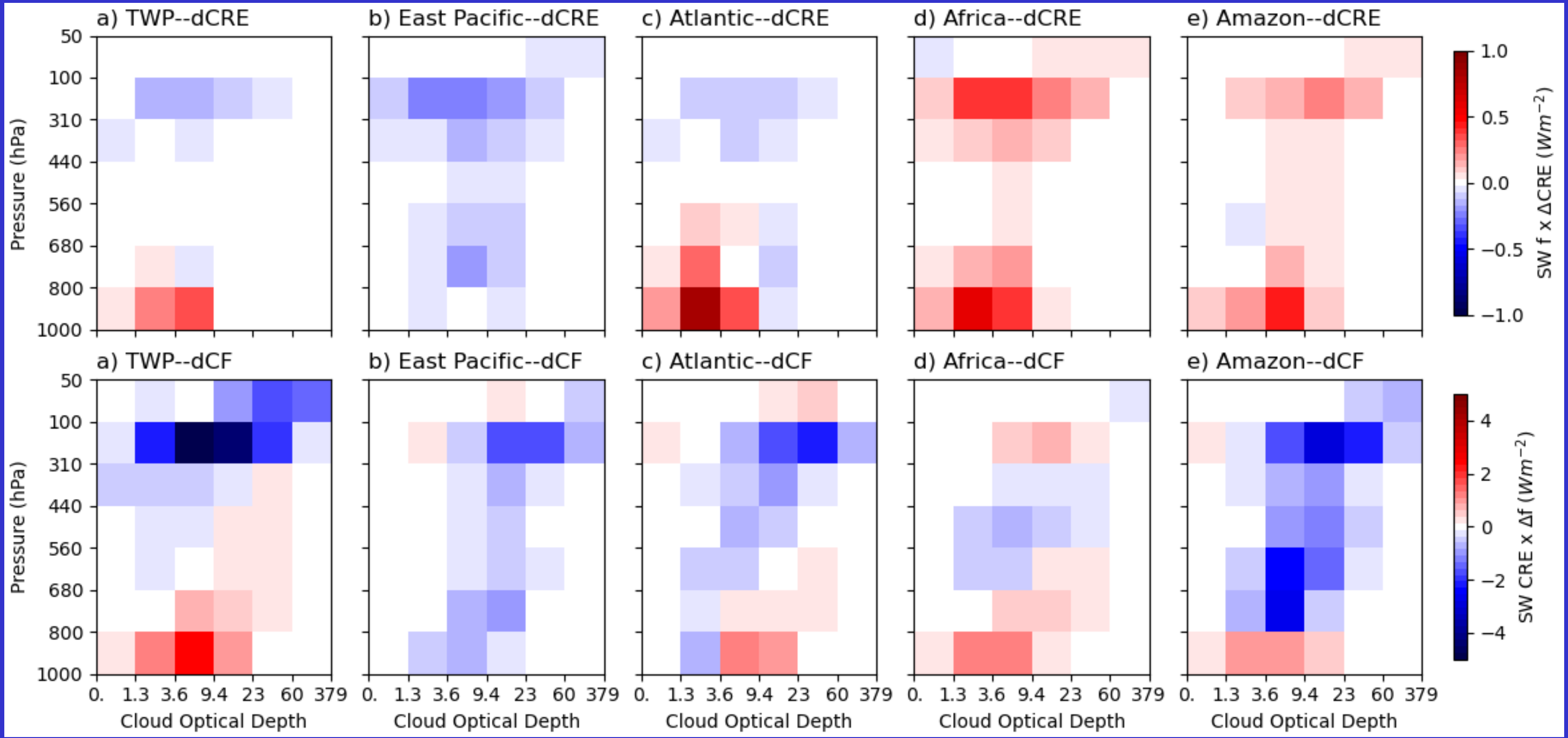


1) For most cloud types, the (LW, SW and net) CRE components are roughly an order of magnitudes smaller than the CF components. (SW and net CRE results are shown later.)
2) The CF component enhances LW warming, with the strongest effect in the TWP and the weakest in Africa

SW CRE decomposition: CRE deviation (top row) and CF deviation (bottom)

$f_{0,j}\ \Delta CRE_j$

$CRE_{0,j}\ \Delta f_j$



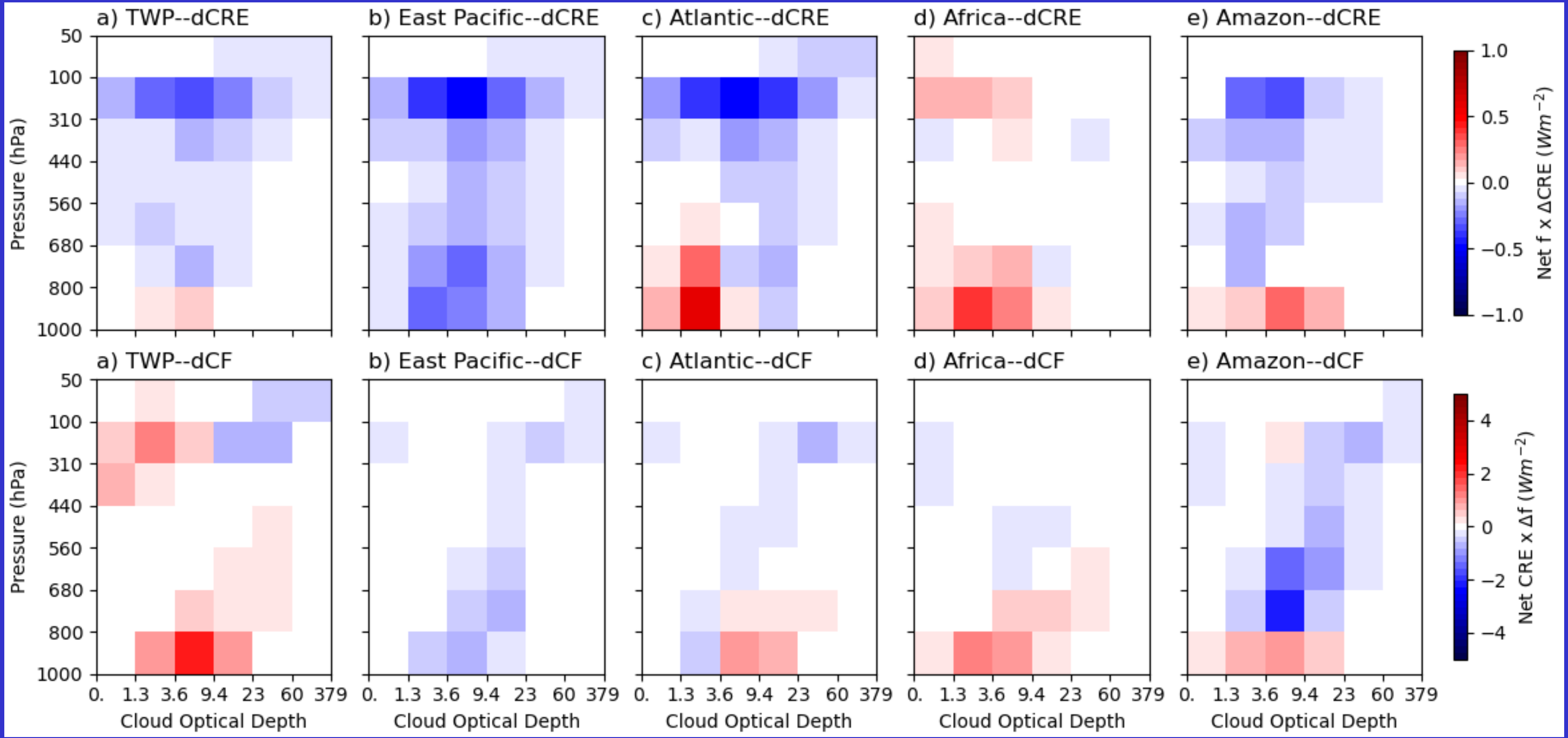
1) The CF component enhances SW cooling, with opposing effects for low clouds and some midlevel clouds;

2) In the CRE component, these opposing effects from low and midlevel clouds are evident only in the TWP and Atlantic regions.

Net CRE decomposition: CRE deviation (top row) and CF deviation (bottom)

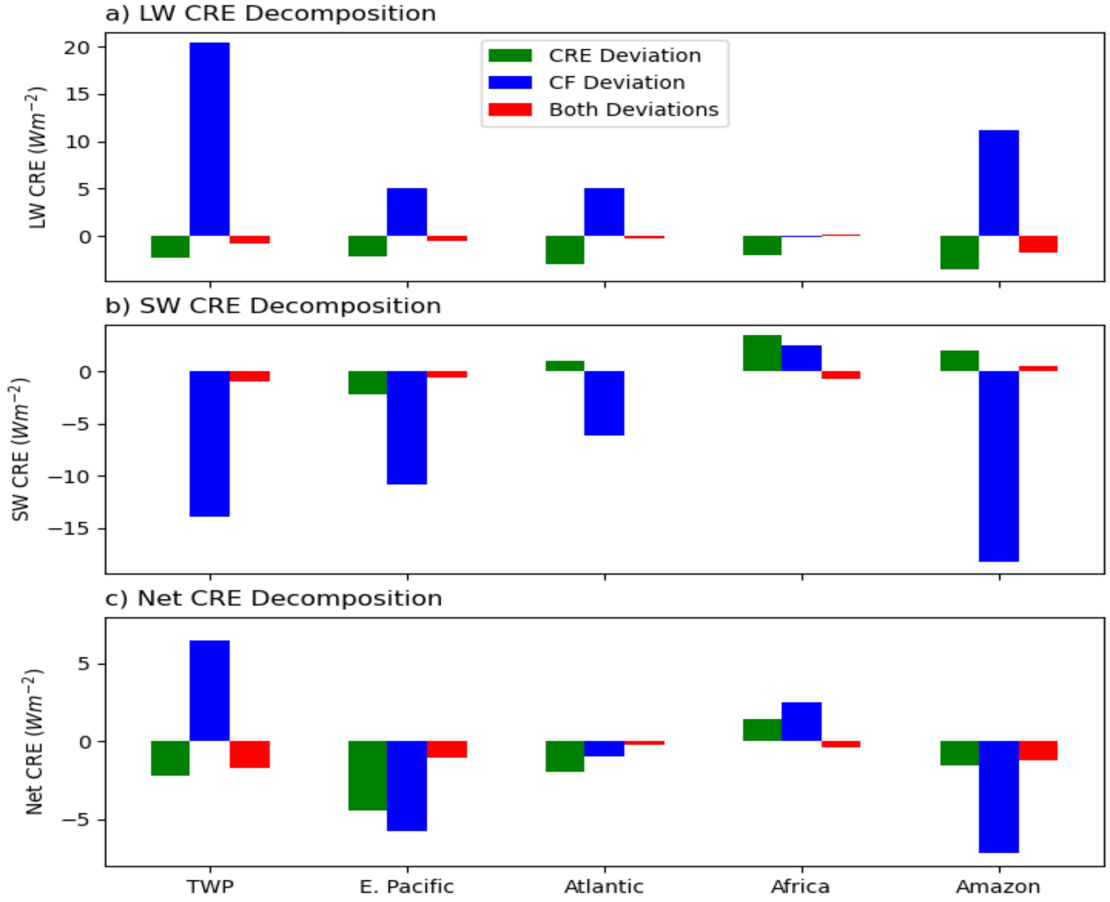
$f_{0,j}\ \Delta CRE_j$

$CRE_{0,j}\ \Delta f_j$

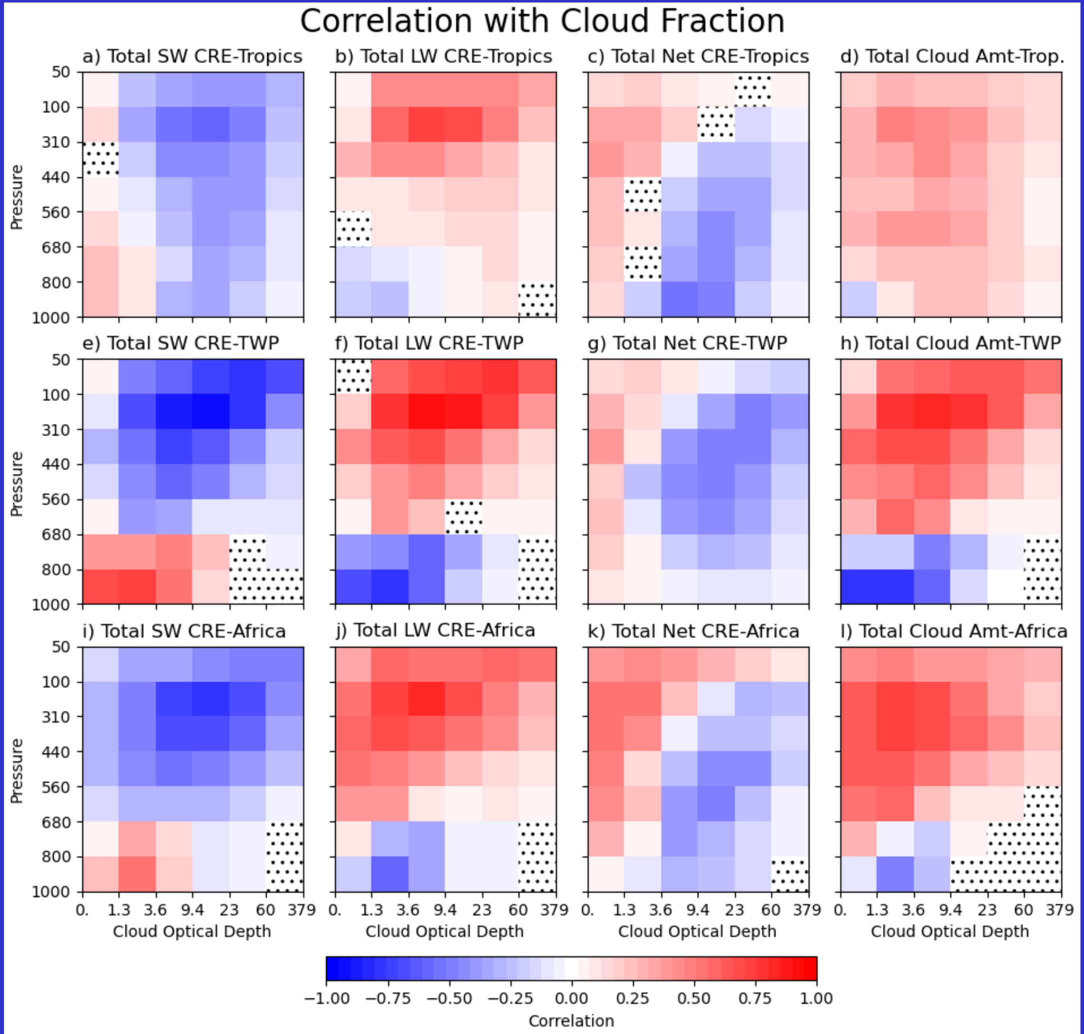


1) Similar to the SW CRE, strong opposing effects between low and high clouds are present in the CF component
2) The CRE deviation component becomes more significant for high clouds, as the influence of the CF component weakens, partly due to the small net mean CRE associated with some high cloud types.

Decomposition of regional total CRE differences from the tropical mean



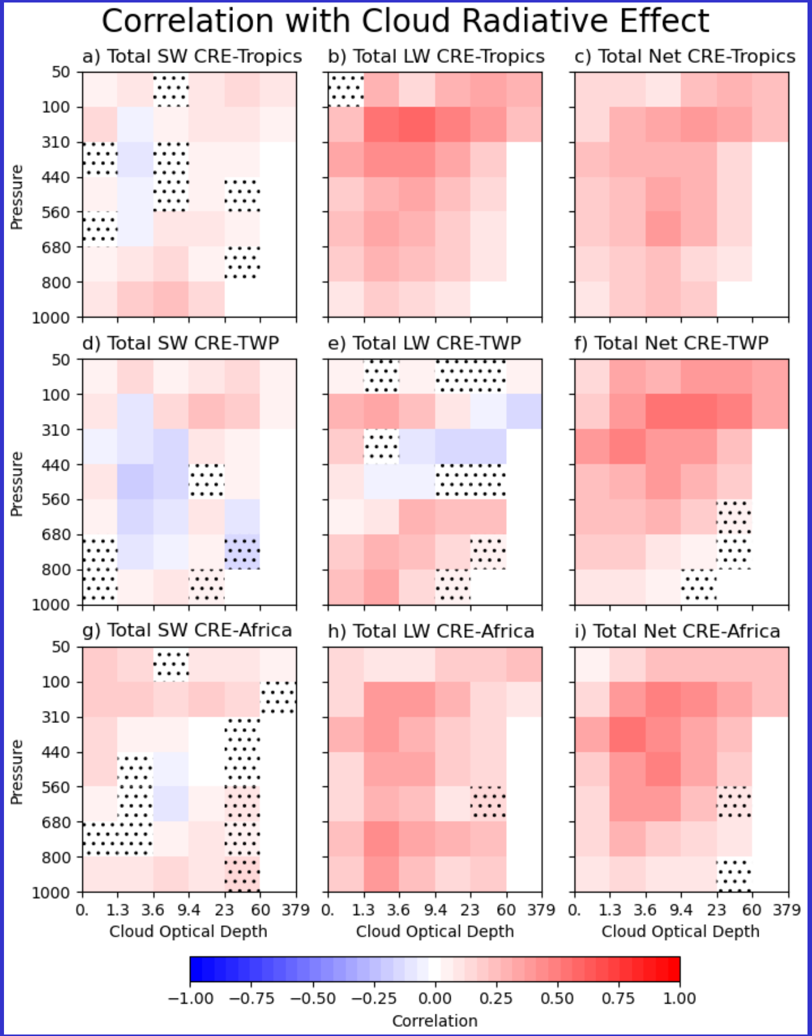
1) The cloud fraction (CF) component, enhancing LW warming and SW cooling, dominates the regional differences in both LW and SW CREs, except in Africa;
2) In Africa, the CRE component is comparable to—or even larger than—the CF component for LW, SW and net CREs;
3) In other regions, the CRE component still contribute significantly to the net CRE differences;
4) Opposing contributions from low- and high-level clouds in the CF component reduce its overall impact on CRE.



Correlations of cloud fraction of individual cloud types with total CREs and total cloud amount

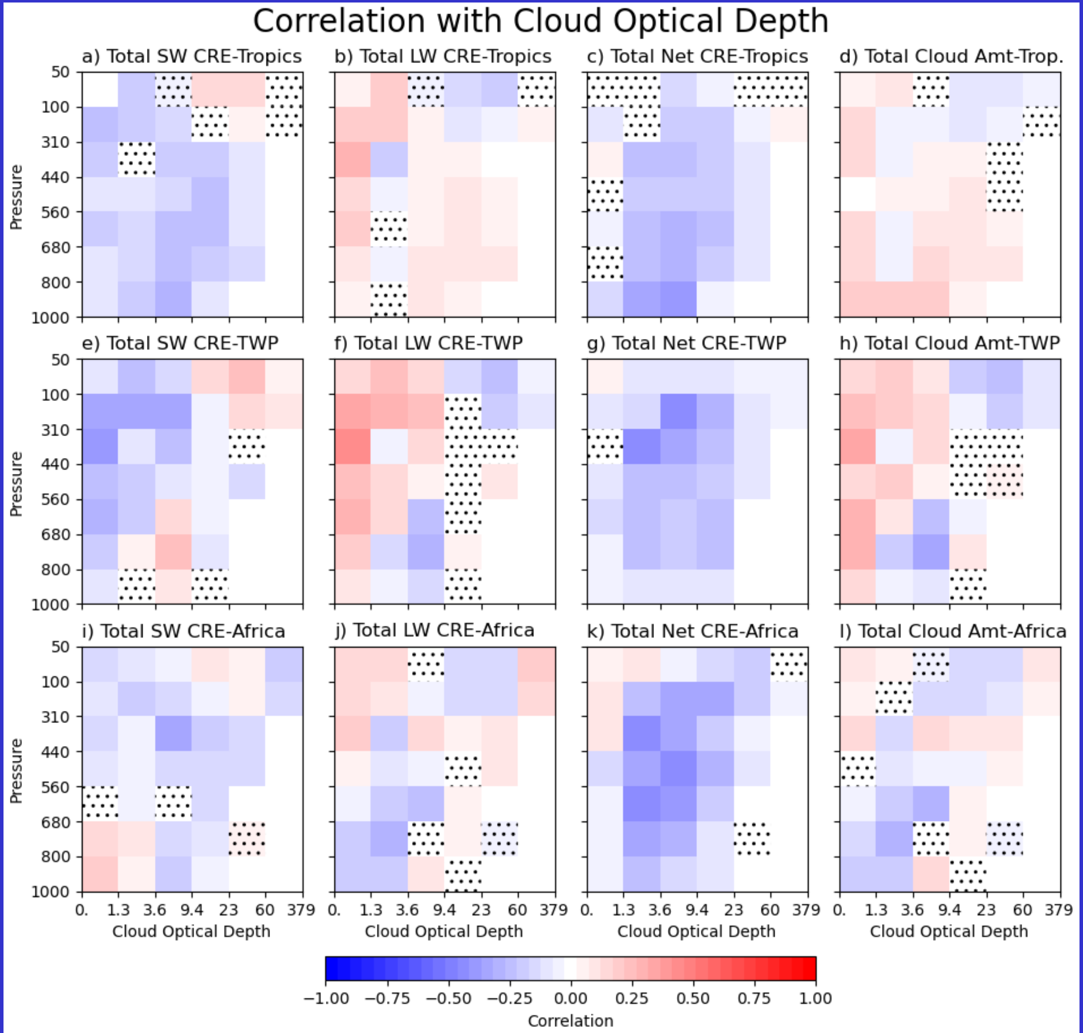
1. Tropics: High clouds strongly drive CRE variability
   - SW CRE: –0.61, LW CRE: +0.75
2. Stronger correlations in TWP & Africa:
   - TWP: –0.90/+0.91, Africa: –0.78/+0.84
   - Notable sign/magnitude changes for low & optically thin (τ ≤ 1.3) clouds
3. Regional drivers:
   - Strong cloud-type links to total cloud amount
   - Correlations up to +0.50 (Tropics), +0.72 (Africa), +0.84 (TWP)
   - Sign reversals for some low cloud types

Dotted areas: insignificant (p > 0.05)



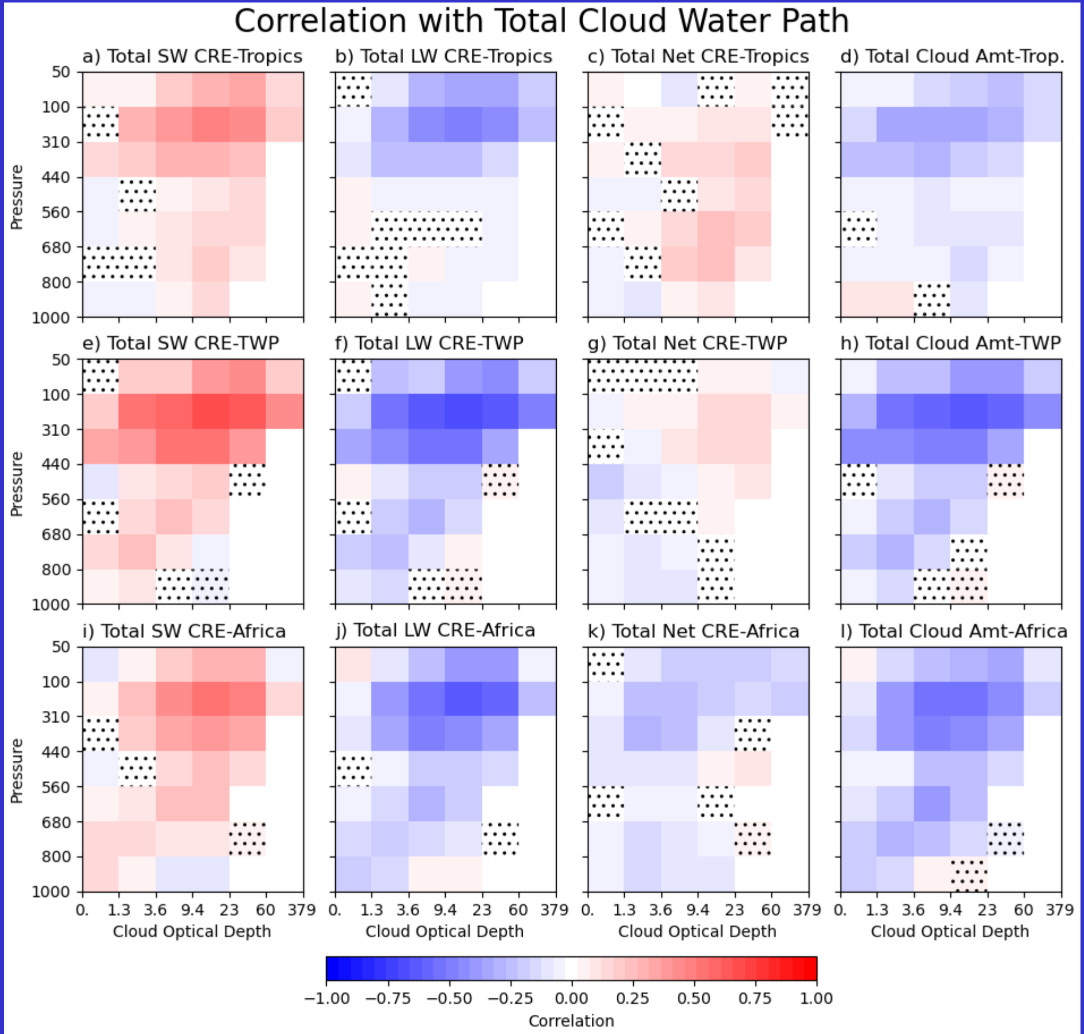
Correlations between the radiative effects of specific cloud types and total CREs

1. SW CRE:
   - Generally weak correlations across all regions
2. LW CRE:
   - Weak in the TWP
   - Moderate for some cloud types: up to 0.58 (tropics,) 0.35 (TWP), and 0.45 (Africa)
3. Net CRE:
   - Moderate for certain cloud types: up to 0.39 (tropics), 0.54 (TWP), and 0.53 (Africa)
4. Key drivers of weak correlations:
   - Limited variability in CRE values by cloud type
   - Total CRE changes mainly driven by shifts in cloud-type distribution

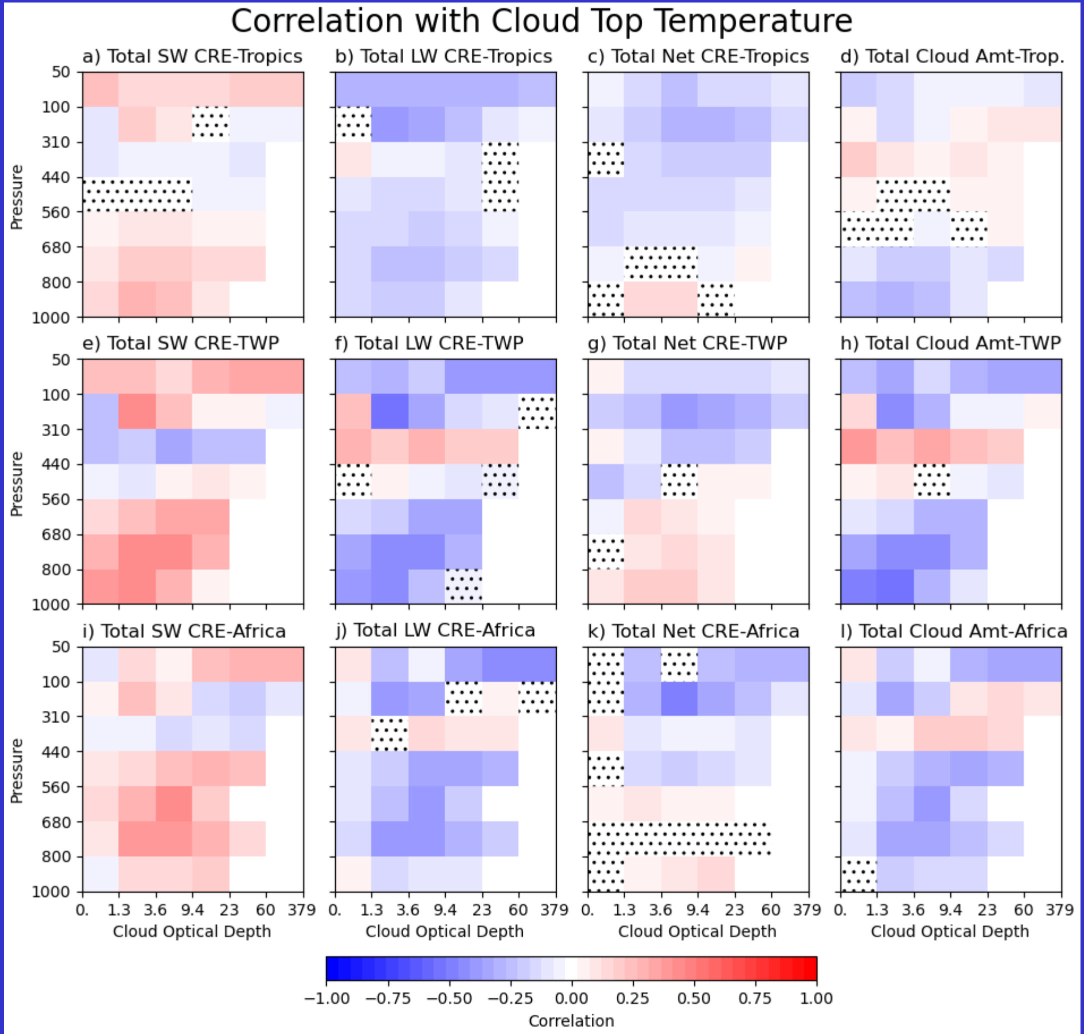


Correlations of cloud optical depth of individual cloud types with total CREs and total cloud amount

- Cloud properties such as total water path, optical depth, and particle size influence cloud type–mean CREs
- However, their correlations with total CRE are relatively weak (see this and next two slides)
- This weakness is largely due to shared variability with total cloud amount, which correlates less strongly with total CRE than the cloud fraction of specific cloud types



Correlations of total cloud water path of individual cloud types with total CREs and total cloud amount



Correlations of effective cloud top temperature of individual cloud types with total CREs and total cloud amount

Summary

- CRE Decomposition analysis:
  - Cloud fraction (CF) deviations dominate, enhancing LW warming and SW cooling for mid/high clouds, but reduce cooling for low clouds.
  - CRE deviations are smaller for most cloud types but contribute significantly to regional net CRE differences due to consistent signals across cloud types.
  - CF effects vary more, influenced by opposing impacts from low vs. high clouds.
  - Regional contrasts driven by land-ocean differences and meteorological forcings.
- CRE Variability analysis:
  - Total CRE variability is mainly driven by cloud fraction, not microphysical properties.
  - High clouds (e.g., cirrostratus, deep convection):
    - Strong −SW / +LW CRE correlations (up to ±0.90 in TWP).
  - Low clouds (e.g., shallow cumulus): Show opposite correlation patterns.
  - Microphysical factors (e.g., optical depth, cloud water path):
    - Weak correlation with total CRE—mostly due to shared variability with total cloud amount.
  - High and low clouds often vary inversely.
  - CRE–cloud relationships are stronger regionally than across the tropical mean.

Publications

- Xu, K.-M., Sun, M., & Zhou, Y., (2024), Analysis of the influence of clear-sky fluxes on the cloud-type mean cloud radiative effects in the tropical convectively active regions with CERES satellite data. *J. Geophys. Res. Atmos., 129,* e2024JD041525. https://doi.org/10.1029/2024JD041525.

- Xu, K.-M., Sun, M., & Zhou, Y., (2025), Comparison of cloud-type properties and radiative effect decomposition in tropical convectively active regions using CERES high-resolution data. *J. Geophys. Res. Atmos.,* (submitted).

- Xu, K.-M., & Sun, M., (2025): Impact and variability of cloud types on Earth's top-of-atmosphere energy balance in the Tropics: A 19-Year analysis of high-resolution CERES data. *J. Geophys. Res. Atmos.,* (submitted).