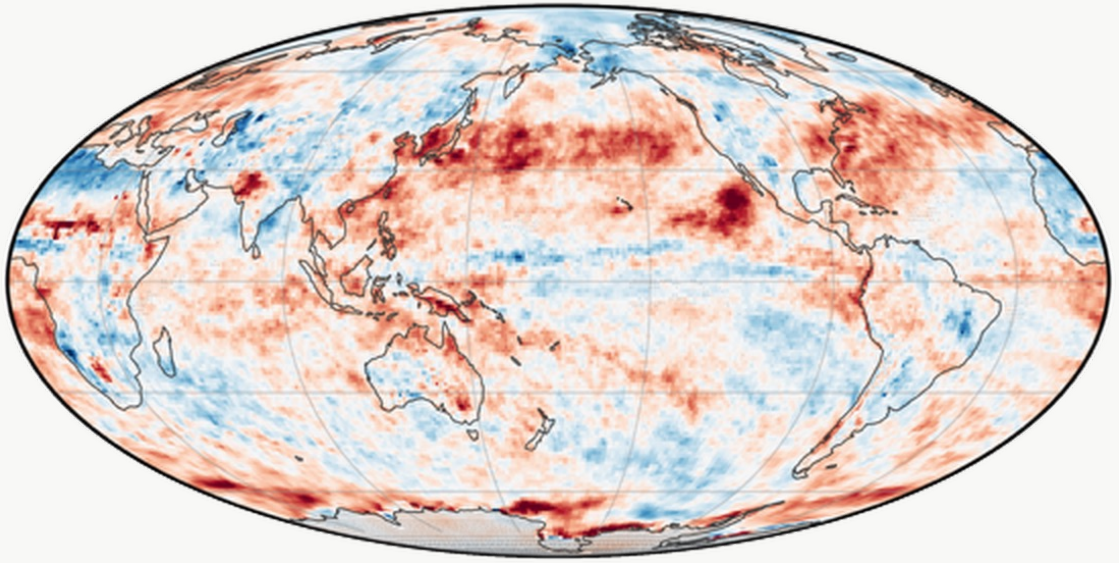
A Cloud System View of the Changing Planetary Energy Budget

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CERES EBAF EEI trend, 2003–2025 (+0.36 W m^{-2} dec^{-1})

CERES Science Team Meeting

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EEI is growing, but which cloud systems are behind it?

- EEI = ASR − OLR is the net energy gain of the Earth system; multiple lines of evidence show it has more than doubled in recent decades (Mauritsen et al. 2025)
- EEI alone does not say whether ASR or OLR is changing, so the two must be examined separately (Loeb et al. 2021, 2024a)
- Clouds act on both: more reflection lowers ASR, more greenhouse trapping lowers OLR
- Global means and grid-point trends cannot tell large, offsetting SW/LW changes from small, reinforcing ones

Questions for this talk

1. Which cloud systems (RORs) carry the 2003–2025 ASR, OLR and EEI trends?
2. Are the trends a population effect (how often a system occurs) or a conditional-state effect (how it behaves when present)?
3. If the latter: location, cloud amount, overcast-cloud properties, or the clear-sky environment?

Data, conventions, and roadmap

Data

- CERES EBAF Ed4.2.1 TOA, monthly 1°: incoming solar, all-sky and clear-sky SW and OLR, total cloud fraction
- MODIS (Terra + Aqua) RORs (=cloud systems) on the same 1° grid
- 2003–2025 (276 months)

Conventions

- EEI = ASR − OLR (positive = Earth gaining energy)
- Figures plot −*OLR*, so positive always means a warming contribution
- Trends: Linear fits to deseasonalized monthly anomalies with 95% CI.

Presentation roadmap

ROR climatological mean state
and radiative characteristics

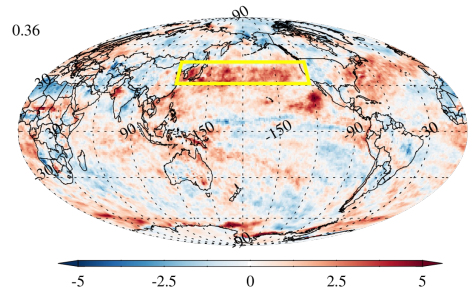
Global trends in ASR, OLR and EEI

ROR contributions to global trends

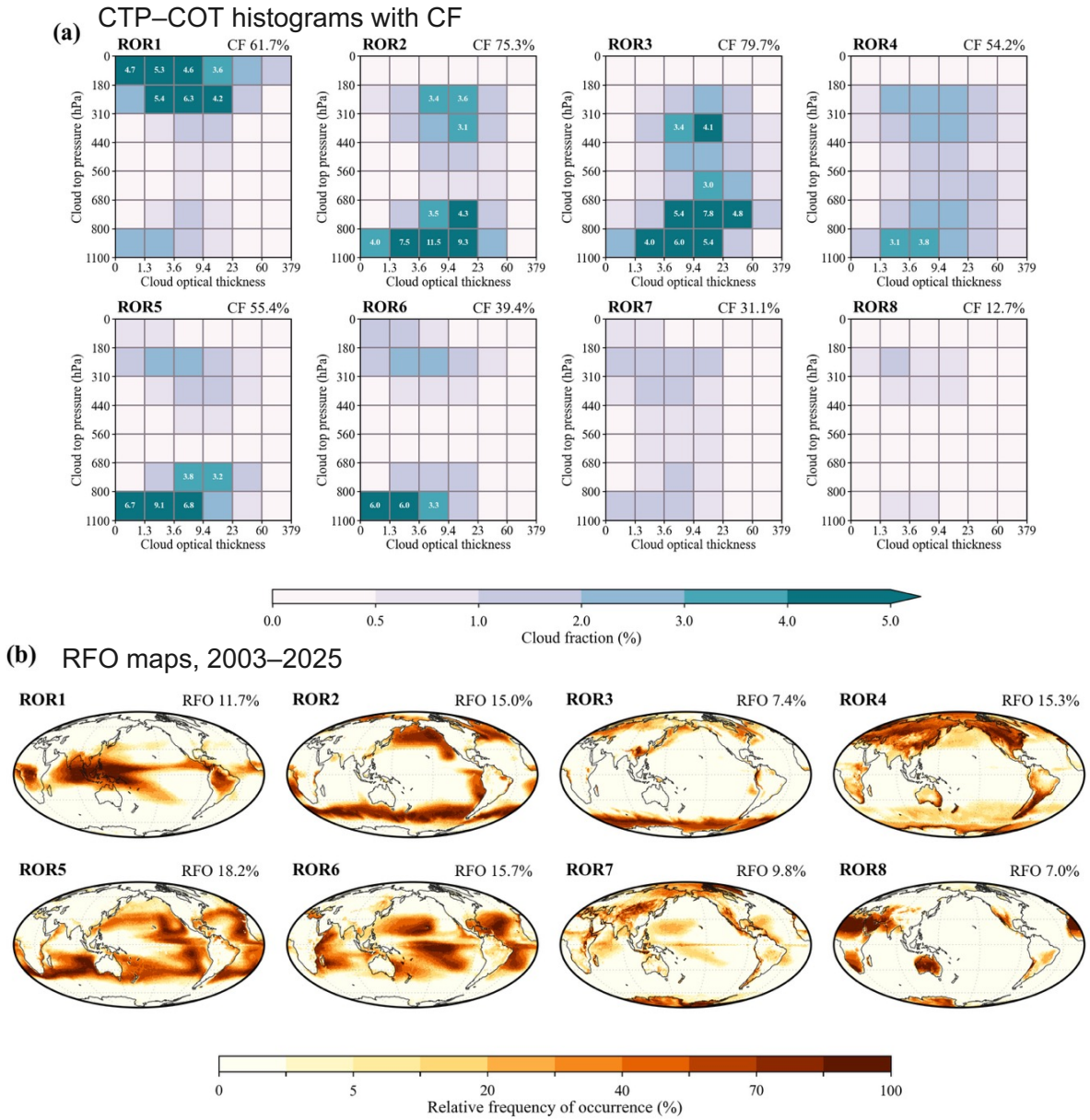
Between- and within-ROR attribution

North Pacific case study

ROR2 spatiotemporal evolution



Regimes of Regimes (RORs): Cloud System states



- Daily 1° MODIS cloud regimes (CTP–COT histograms, k-means; Cho et al. 2021) → regime frequencies in 3-month windows (Terra + Aqua) → 8 RORs (Cho et al. 2025)

ROR	Cloud system environment	CF (%)	RFO (%)
1	Tropical convection	61.7	11.7
2	Midlatitude oceanic storm tracks	75.3	15.0
3	High-latitude thick cloud systems	79.7	7.4
4	Continental midlevel cloud systems	54.2	15.3
5	Subtropical shallow marine (Sc)	55.4	18.2
6	Subtropical shallow convection	39.4	15.7
7	Suppressed, low cloud fraction	31.1	9.8
8	Arid or nearly clear	12.7	7.0

- No single ROR dominates globally: RFO ranges 7.0–18.2%

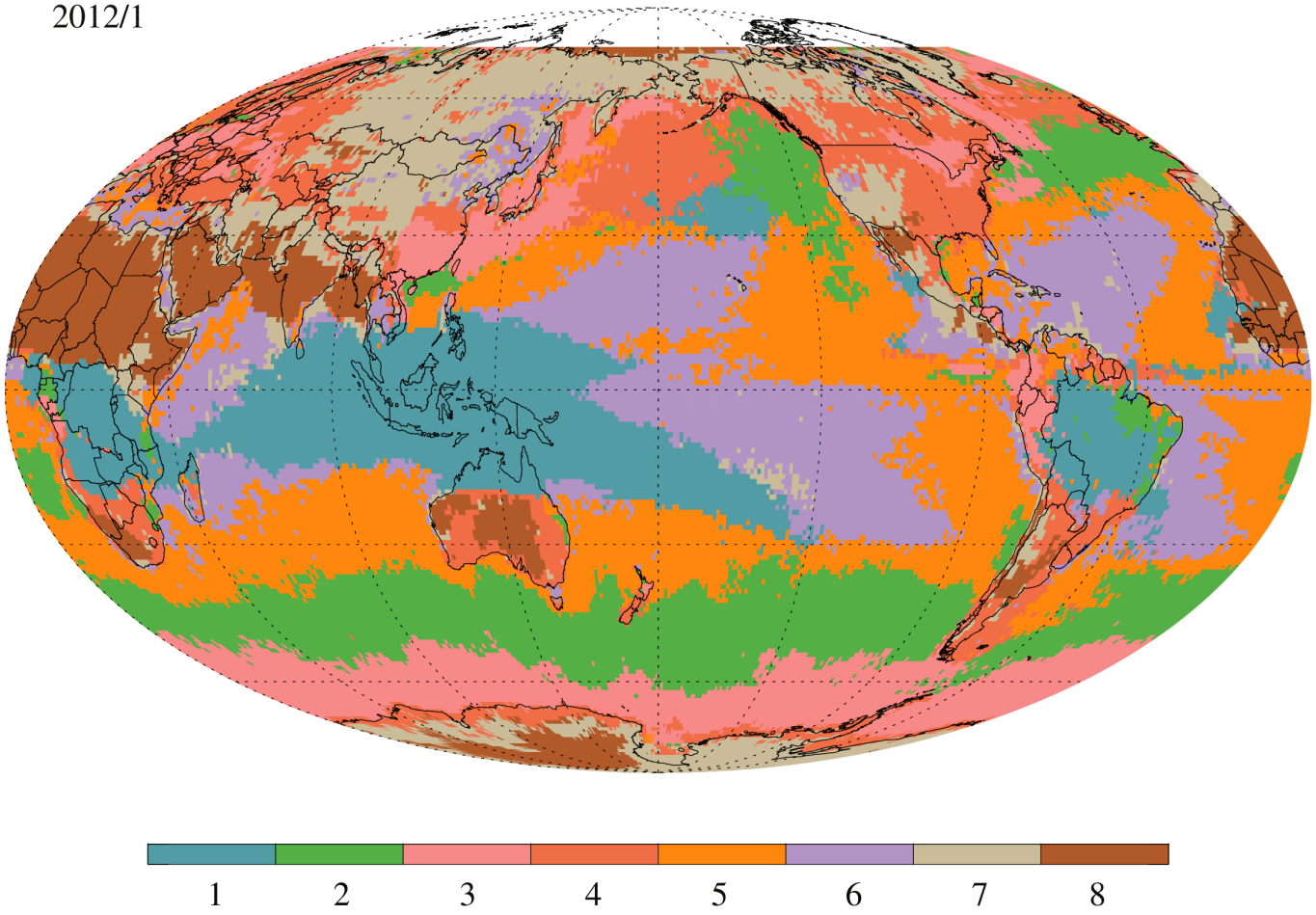
Regimes of Regimes (RORs): Cloud System states Seasonal Cycle

ROR1
tropical convective

ROR2
mid-lat oceanic storm track

ROR3
high-lat thick stratus

ROR4
mid-lat continental mid-level



ROR5
subtropical shallow marine

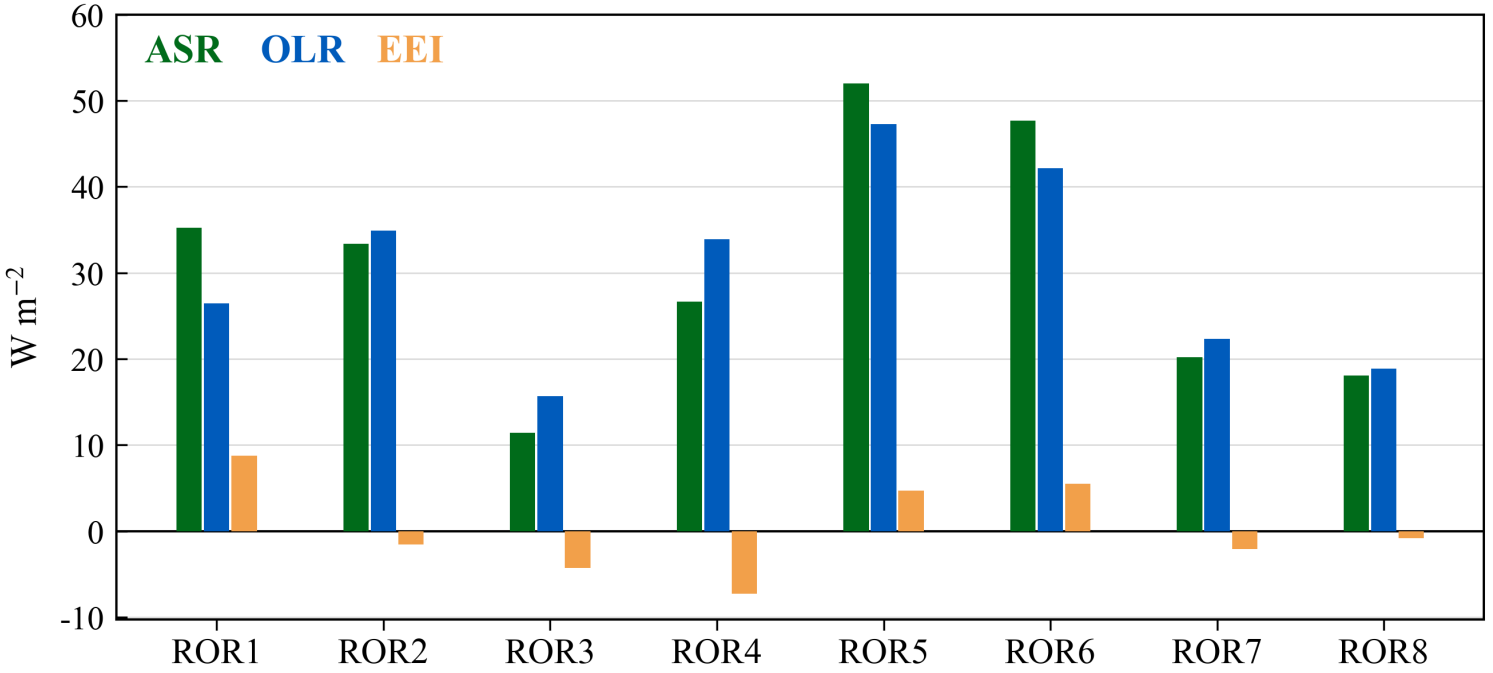
ROR6
subtropical shallow convection

ROR7
suppressed low CF

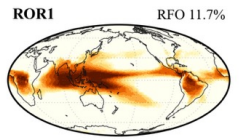
ROR8
arid almost clear

Large ASR and OLR contributions do not imply a large EEI contribution.

ROR climatological mean state
and radiative characteristics

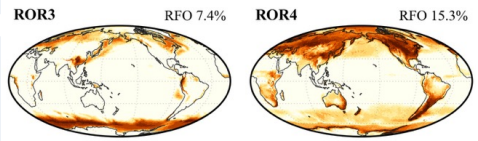


RFO-weighted global-mean ASR, OLR and EEI by ROR (W m^{-2}).
Global totals: 241.4, 240.5, 0.9



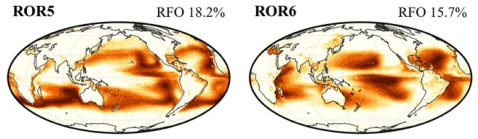
ROR1 tropical convection

Largest positive EEI (+8.8 W m^{-2}): deep convective cloud lets little LW escape



ROR3, ROR4
high-latitude, continental

Negative EEI (−4.3 and −7.2 W m^{-2}): OLR exceeds ASR



ROR5, ROR6
subtropical low cloud

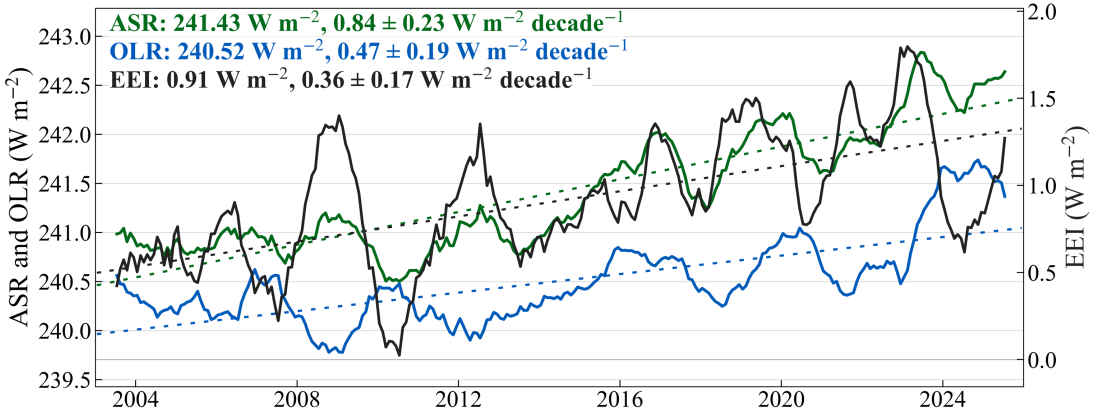
Largest ASR (52.0, 47.7) and OLR (47.3, 42.2) contributions, yet only +4.7 and +5.5 W m^{-2} in EEI

SW and LW partly offset within regimes, so EEI alone hides how much each regime is doing.

2003–2025: EEI rises by 0.36 W m⁻² per decade, led by ASR

Global trends in ASR, OLR and EEI

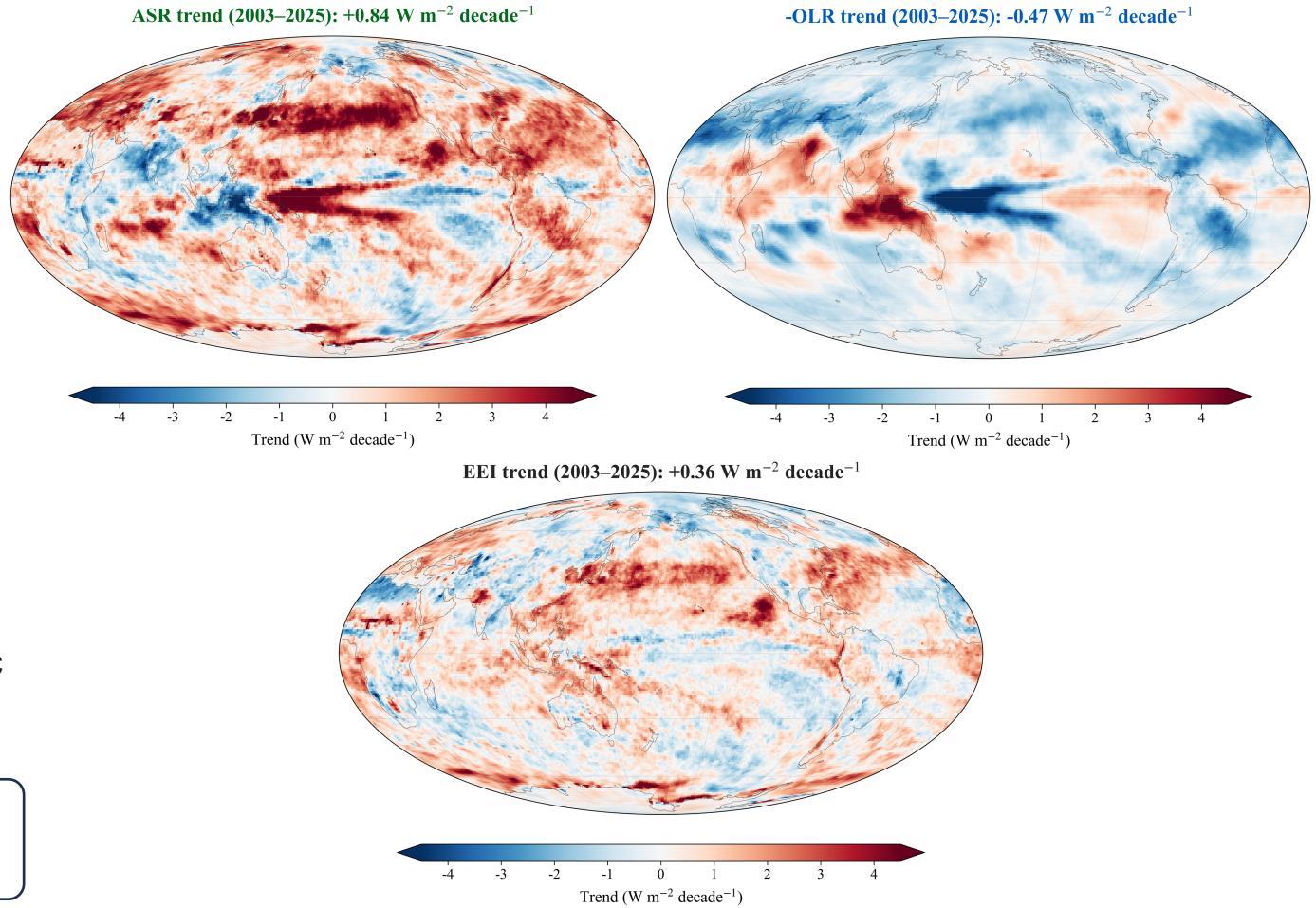
global anomalies, 12-month running mean



- ASR increase ≈ 1.8 × OLR increase: a growing surplus, not a cancellation
- Area-weighted means of the trend maps reproduce the time-series trends
- Strong, opposing ASR and −OLR trends recur in specific places (e.g., tropical Indo-Pacific)

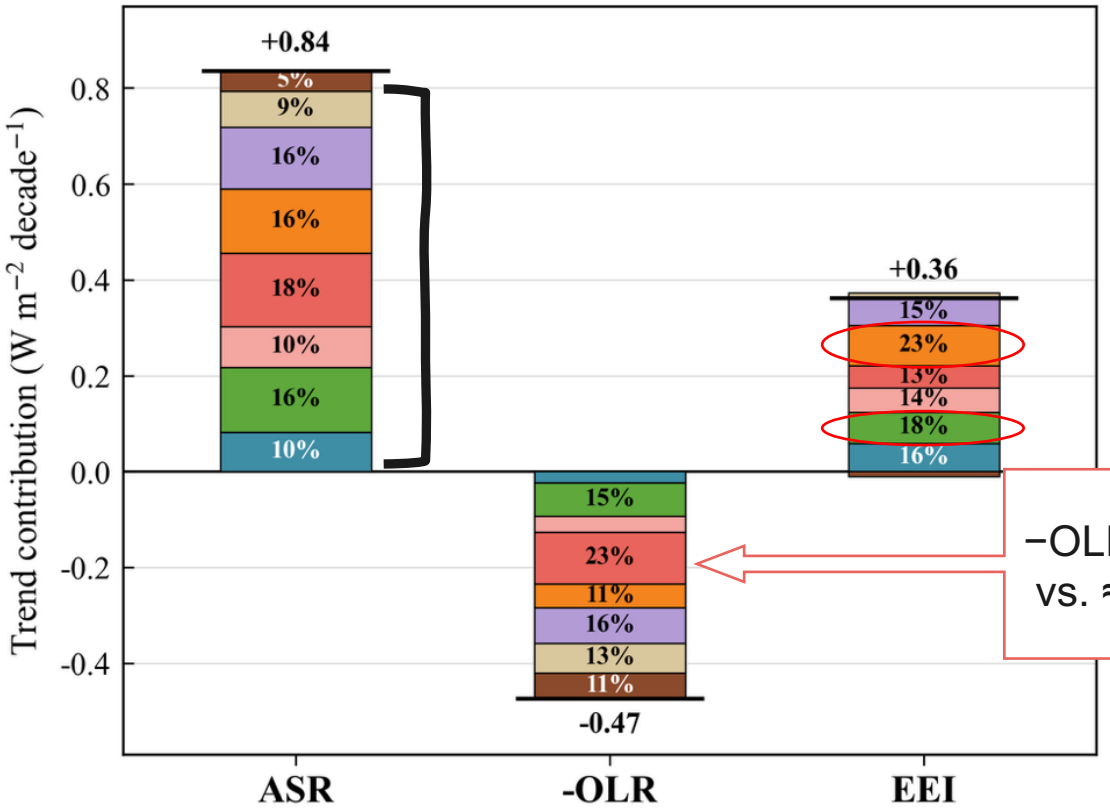
Recurrent regional compensation hints at an organizing structure.

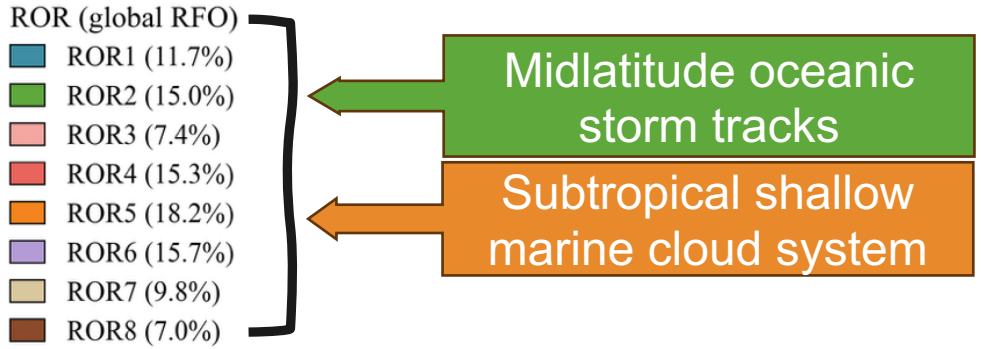
trend maps (positive = warming)



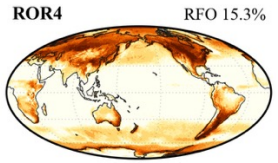
Fixed climatological footprints show where the trends are expressed

ROR contributions to global trends





−OLR: ROR4 footprint ≈ 23% of the total vs. ≈ 15% RFO



Contributions of fixed ROR footprints to global trends
(% of total; W m^{-2} dec^{-1} at top)

Each ROR's climatological RFO map × trend map: occurrence and location held fixed.
Shows where the trends occur, but not how changing cloud systems produce them.

Trend decomposition

Between- and within-ROR attribution

$$\Delta F = \underbrace{\sum_r \bar{F}_r \, \Delta RFO_r}_{between} + \underbrace{\sum_r \overline{RFO}_r \, \Delta F_r}_{within}$$

r : ROR, $\bar{X}$: 2003–2025 mean, Δ: linear trend.
The covariance term is neglected (minor).

Between *(Population effect)*

The ROR becomes more or less frequent globally while keeping its mean flux (= how often a cloud system occurs)

Within *(Conditional state effect)*

The ROR's flux changes while it is present; its occurrence weight is held fixed (= how and where it behaves when it occurs)

Spatial translocation

ROR samples a different part of the fixed climatological flux field (brighter or darker, warmer or colder places)

Climatological flux resampled with the time-varying ROR mask

Microphysical (overcast cloud)

Overcast-cloud radiative state at fixed cloud amount: τ, water path, r_e, cloud-top height/T

$$C_{i,m(t)}\left[F_{i,t}^{ovc} - F_{i,m(t)}^{ovc}\right]$$

Macrophysical (cloud fraction)

Cloud-amount anomaly against the climatological overcast–clear contrast

$$\left[C_{i,t} - C_{i,m(t)}\right]\left(F_{i,m(t)}^{ovc} - F_{i,m(t)}^{clr}\right)$$

Environmental (clear sky)

Clear-sky changes at fixed cloud amount: aerosol, water vapor, T, GHGs, sea ice, surface albedo

$$\left(1 - C_{i,m(t)}\right)\left[F_{i,t}^{clr} - F_{i,m(t)}^{clr}\right]$$

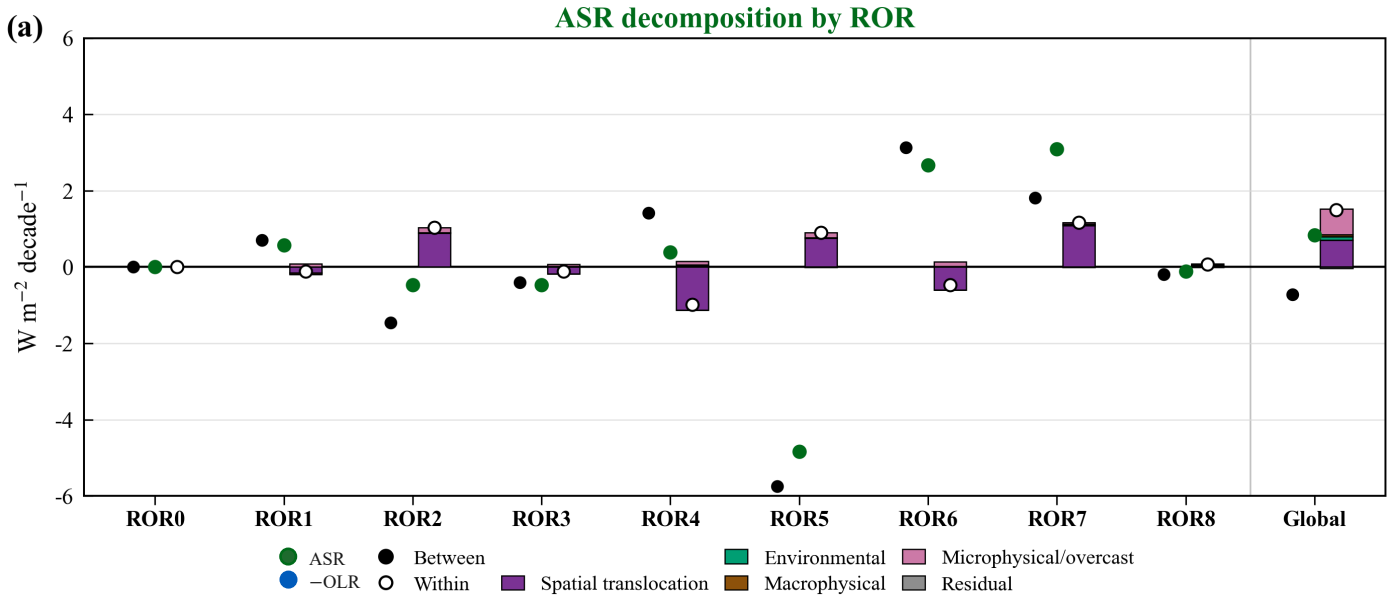
Residual

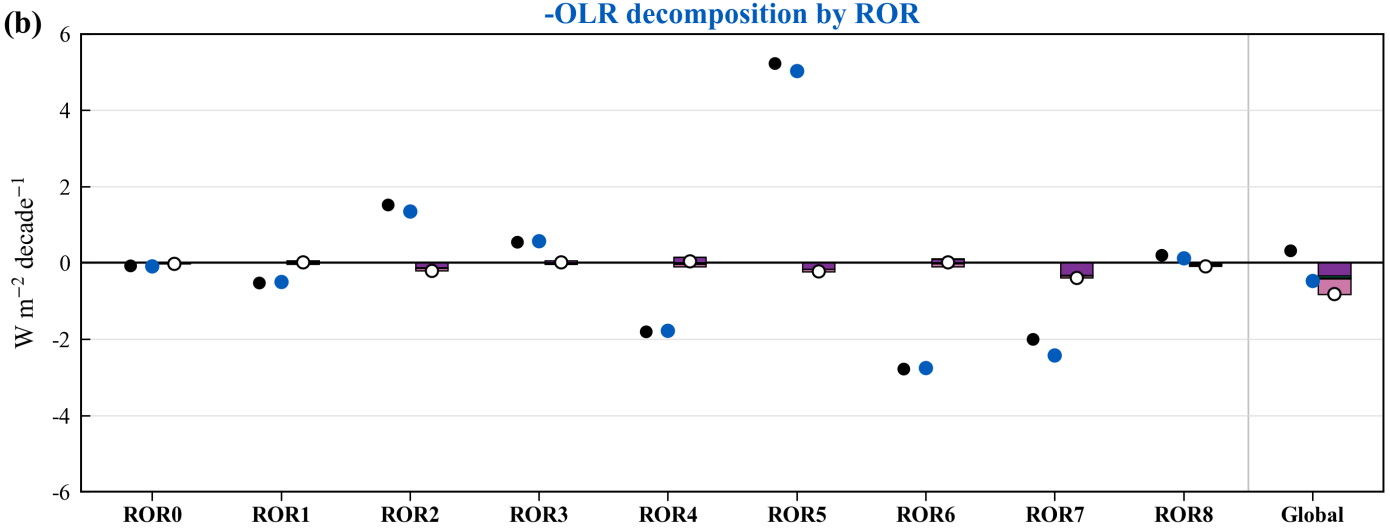
Part of the local all-sky anomaly not captured by the three local terms

This is not a cloud-feedback decomposition.
RORs are coupled cloud–circulation–thermodynamic states, and the within term keeps cloudy and clear parts together.

ASR, −OLR trend decomposition by ROR

Between- and within-ROR attribution





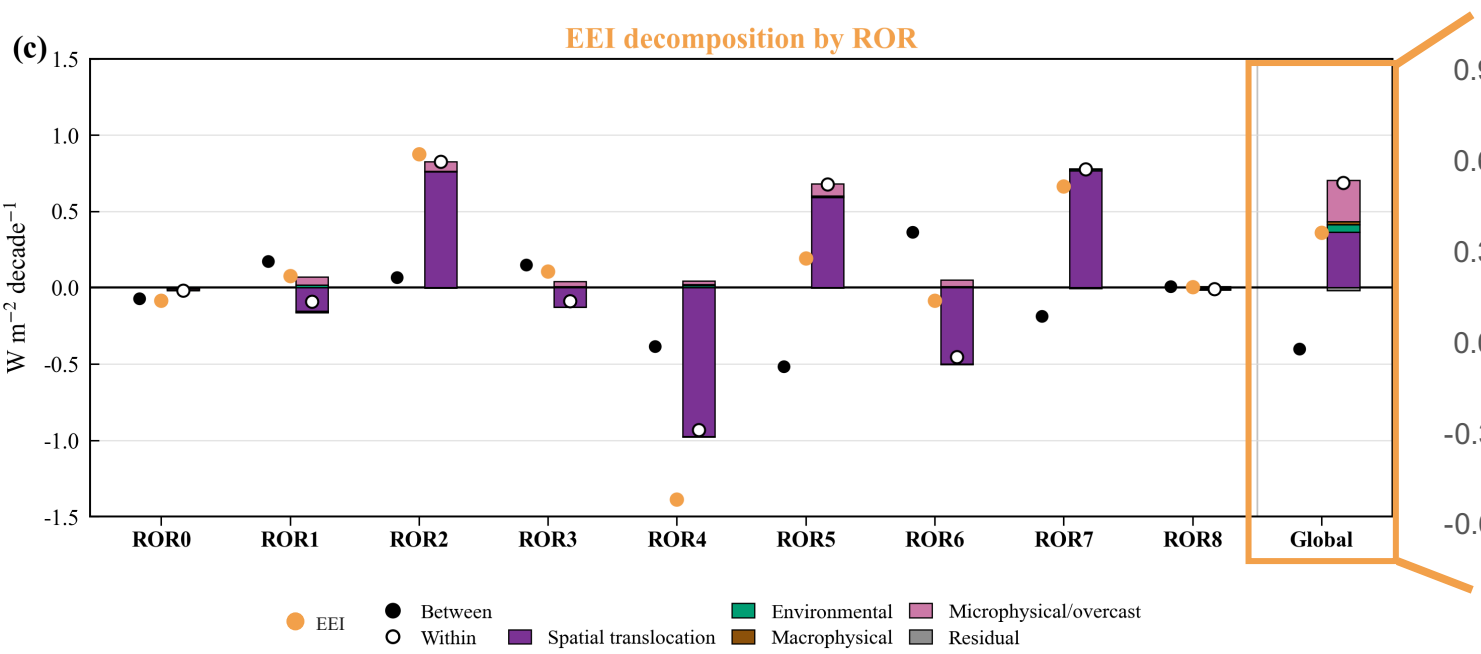
black dot = between; open = within;
colored dot = total ASR or −OLR; bars = within components

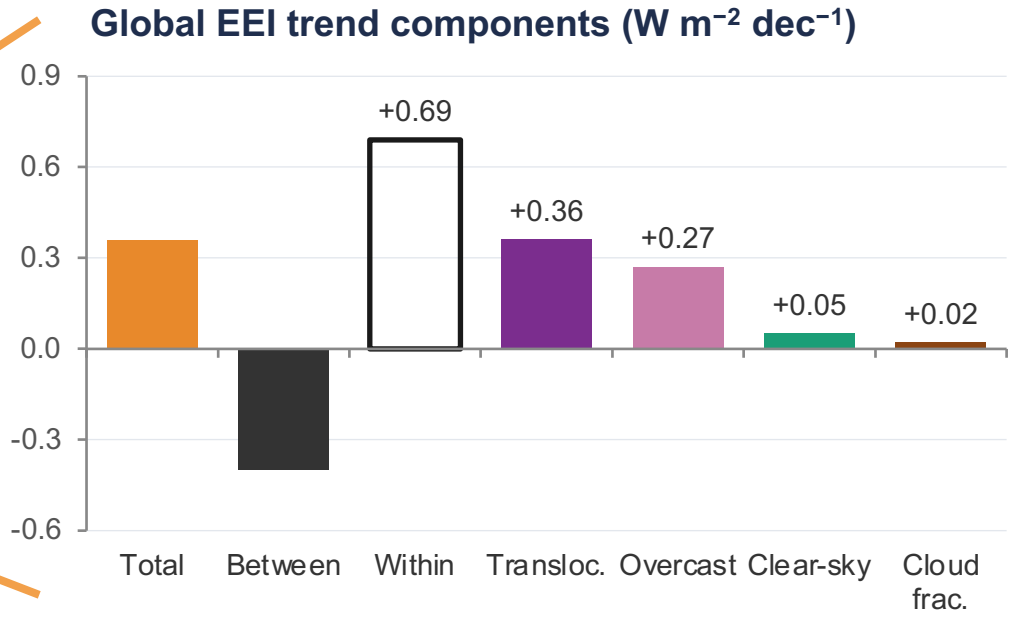
- Between term = $\bar{F}_r\ \Delta RFO_r$: set by how fast occurrence changes and how bright or warm the ROR is
- RFO is a closed set ($\sum_r \Delta RFO_r \approx 0$): the global between term depends on which RORs trade places
- $\overline{ASR}_r > 0$ but $-\overline{OLR}_r < 0$, so one ΔRFO_r gives opposite-sign SW and LW between terms
- ROR5 (largest RFO decline) and ROR6 show the largest opposing pairs; ROR4 and ROR7 smaller

Between terms are large in ASR and −OLR but largely self-cancel in EEI.

EEI trend decomposition by ROR

Between- and within-ROR attribution





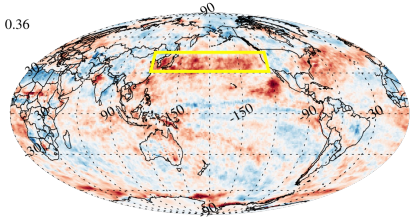
By ROR

- ROR2 and ROR7 lead the positive side
- ROR4 leads the negative side
- Translocation is often the largest within-ROR component, but about 90% of the opposing contributions cancel globally.
- Microphysical contributions are smaller for individual RORs but mostly positive, so they add up with little cancellation globally.

Global

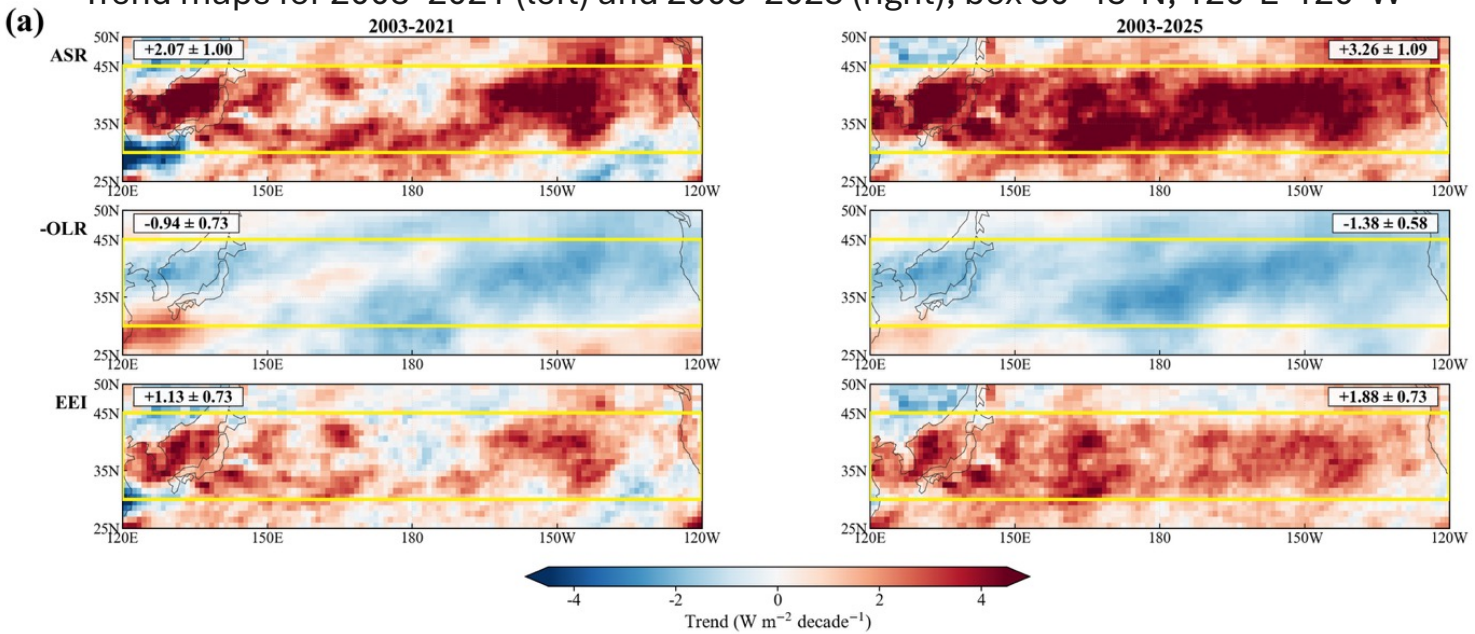
- The positive within-ROR contribution outweighs the negative between-ROR contribution, driving the global EEI increase.
- This mainly reflects RORs sampling radiative environments that contribute more positively to EEI over time, together with changes in their overcast-cloud properties at fixed cloud amount.

North Pacific: 3.5% of Earth's area, 18% of the global EEI trend



North Pacific case study

Trend maps for 2003–2021 (left) and 2003–2025 (right); box 30–45°N, 120°E–120°W



Trend change, 2025 minus 2021 endpoint (W m^{-2} dec^{-1})

	Total	Between	Within
ASR	+1.19	**+0.94**	+0.27
−OLR	−0.44	**−0.20**	−0.25
EEI	+0.75	**+0.73**	+0.02

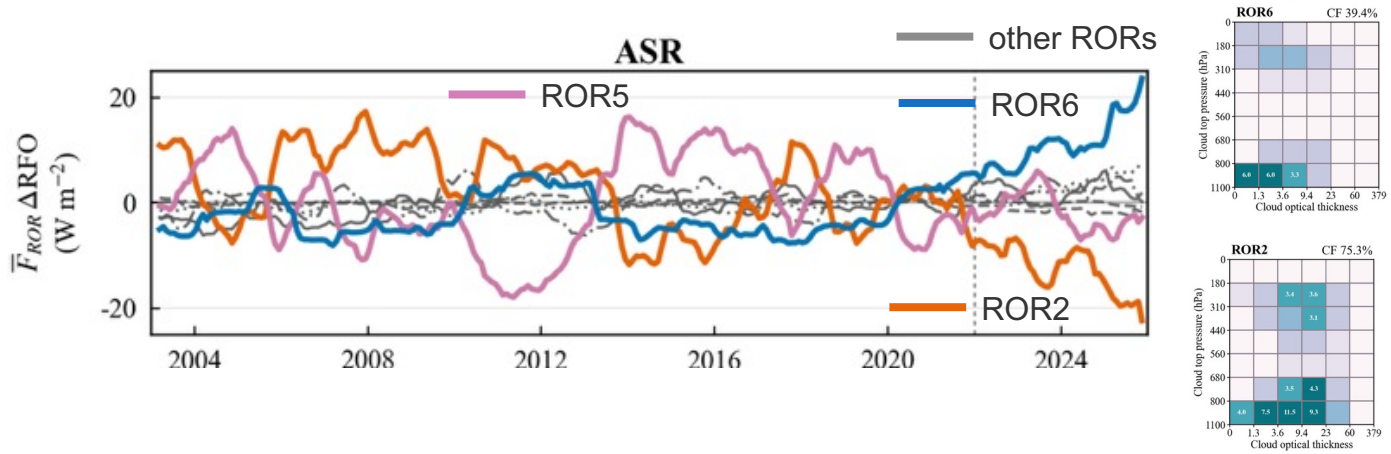
Between contribution to the change

79% of ΔASR and 97% of ΔEEI

= Flux trend change caused by changes in cloud system(ROR) characteristics in this region.

After 2021, the North Pacific shifts from ROR2 toward ROR6

Between-ROR contributions. dotted line = end of 2021



Summary

1. The 2003–2025 EEI trend (+0.36 ± 0.17 W m^{-2} $decade^{-1}$) reflects a reorganization of cloud systems, not one dominant process

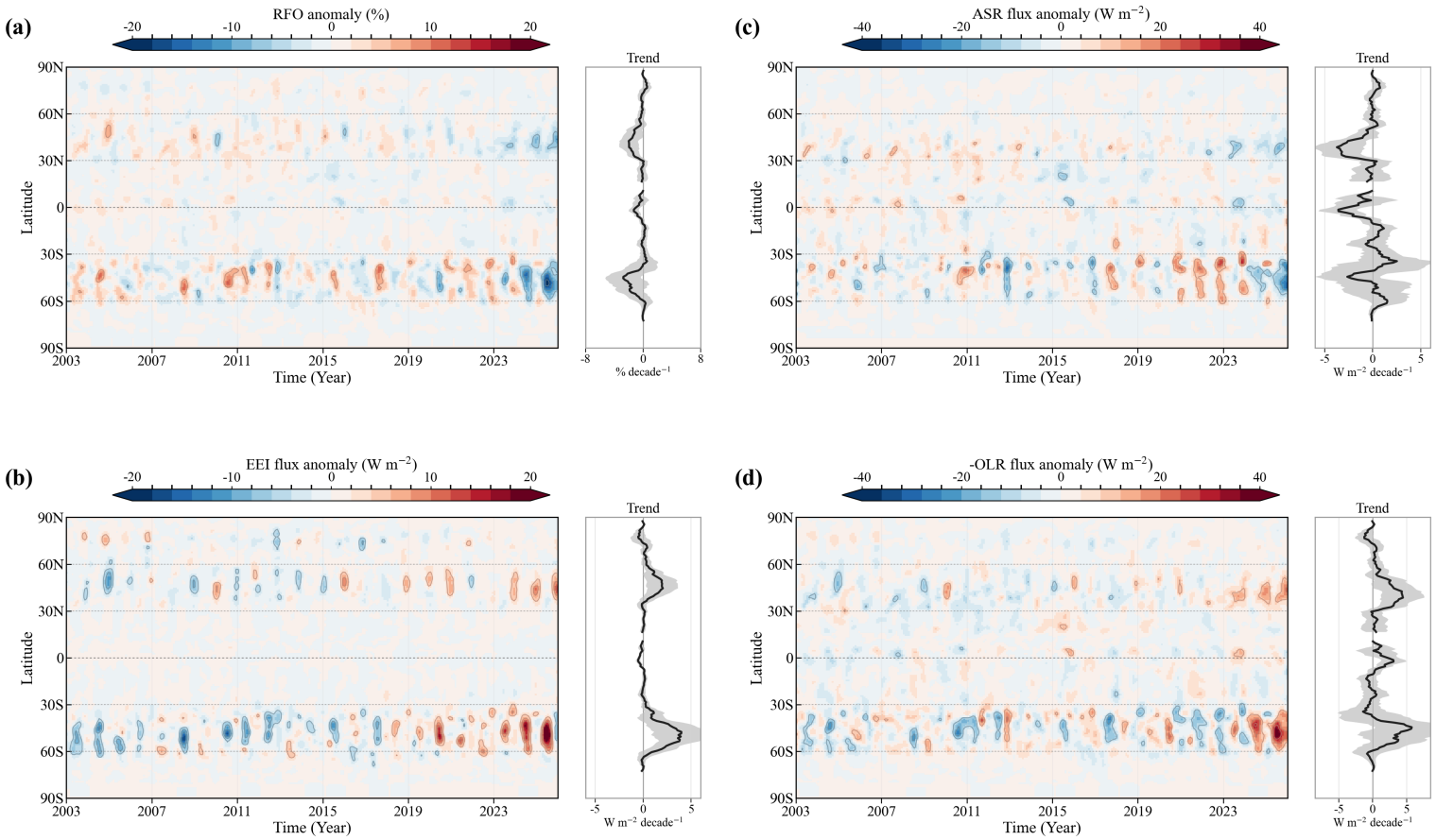
2. ROR2 (storm tracks) and ROR7 (suppressed low CF) lead the positive contributions, while ROR4 (continental midlevel) makes the largest negative contribution. ROR5 (Subtropical shallow marine) shows strong SW–LW cancellation.

3. Globally, within (+0.69) outweighs between (−0.40); within is driven mainly by translocation (+0.36) and overcast-cloud properties (+0.27), with little contribution from cloud fraction (+0.02)

4. North Pacific: ASR trend 2.1 → 3.3 W m^{-2} $decade^{-1}$ (2021 → 2025 endpoint), mostly a shift toward more absorptive regimes

5. The framework identifies where and through which radiative pathways the EEI trend appears, but the underlying causes, including changes in aerosol indirect effect, atmospheric circulation, and cloud-controlling factors, require independent testing.

ROR2: fewer occurrences, yet stronger EEI over the Southern Ocean



ROR2 Hovmöllers of (a) RFO, (b) EEI, (c) ASR, (d) −OLR anomalies, with zonal trends and 95% CI

- 30–60°S: RFO anomalies turn negative in recent years, giving a negative RFO trend
- EEI anomalies: robust, intensifying positive signal in the same band
- Between contribution to ROR2's EEI trend ≈ 0, so the trend comes from the within term
- Within-ROR2 is mostly SW; the LW within term weakly opposes it (Fig. 5)
- Hovmöllers mix between and within at every point, which explains the noisy ASR panel

One regime definition links the space–time pattern to a quantified radiative pathway.

Backup: within-term definitions and closure

Component	Local field or definition
Overcast flux	F_{ovc} from $F = (1 - C)\,F_{clr} + C\,F_{ovc}$; $C \rightarrow \max(C, 0.01)$ in the denominator
Microphysical	$W^{micro} = C_{clim}\,(F_{ovc} - F_{ovc,clim})$
Macrophysical	$W^{macro} = (C - C_{clim})\,(F_{ovc,clim} - F_{clr,clim})$
Environmental	$W^{env} = (1 - C_{clim})\,(F_{clr} - F_{clr,clim})$
Residual	$W^{res} = (F - F_{clim}) - W^{micro} - W^{macro} - W^{env}$
ROR aggregation	$\Delta W^{X}_{r} = \langle RFO \rangle_{r} \cdot \beta[\, \Sigma_i\, \delta_r\, W^{X}\, g \,/\, \Sigma_i\, \delta_r\, g\,]$
Translocation	$f_{r,t} = \Sigma_i\, \delta_r(i,t)\, F_{i,m(t)}\, g \,/\, \Sigma_i\, \delta_r\, g$; $\Delta W^{trans}_{r} = \langle RFO \rangle_{r} \cdot \beta[\, f_{r,t} - f_{r,m(t)}\,]$

clim: calendar-month climatology at each grid cell; δ_r: ROR mask; g: area × month-length weight; β: OLS trend

Global closure error (W m^{-2} dec^{-1})

Flux	Error
ASR	−0.0016
−OLR	+0.0008
EEI	−0.0008

Within term computed directly ($\langle RFO \rangle_t \Delta F_r$) vs. sum of five components

After 2021, the North Pacific shifts from ROR2 toward ROR6

North Pacific case study

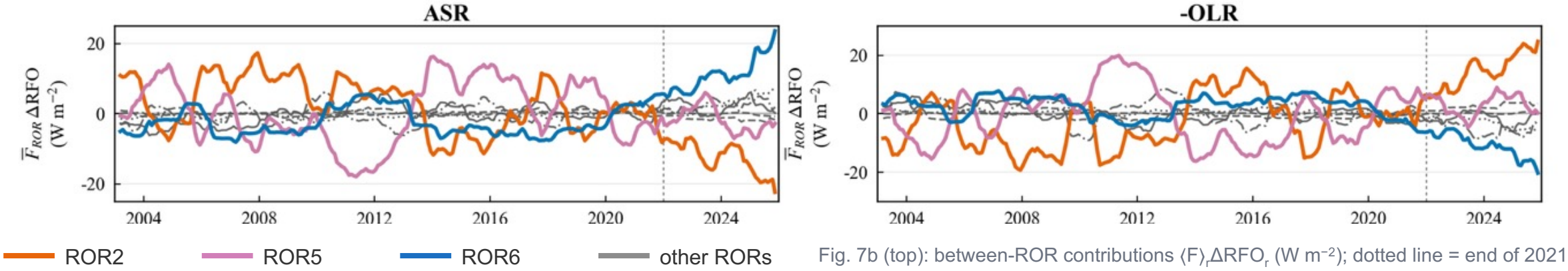


Fig. 7b (top): between-ROR contributions $\langle F \rangle_r \Delta RFO_r$ (W m^{-2}); dotted line = end of 2021

ROR2 (mostly frontal, high CF)

- Between ASR trend: −5.55 → −9.23 W m^{-2} dec^{-1}
- Within ASR trend also rises: +0.89 → +1.12, so its radiative state changes too

ROR6 (lower CF, more absorptive)

- Regional mean ASR 279 vs. 248 W m^{-2} for ROR2
- Between ASR contribution grows more positive as the record is extended

Net effect

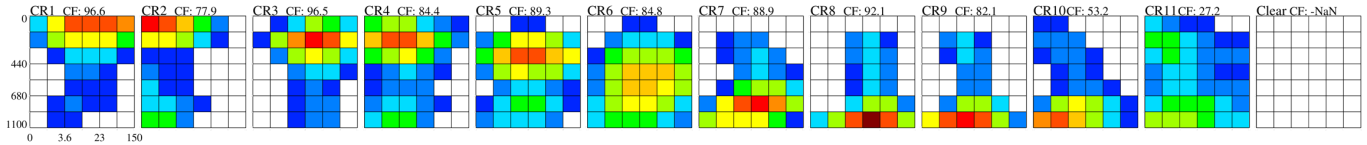
- For both RORs, ASR and −OLR between terms move oppositely and partly offset
- Leaves a modest positive between-EEI trend

Take-away Population replacement, plus a SW increase within ROR2, underlies the North Pacific acceleration.

Passive Views

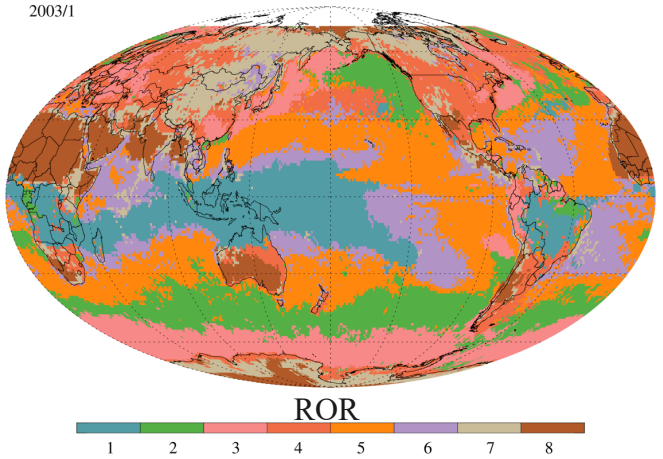
Regimes of Regimes (RORs) : Monthly

- Including daily variability of cloud features
- Temporal coverage of MODIS dataset

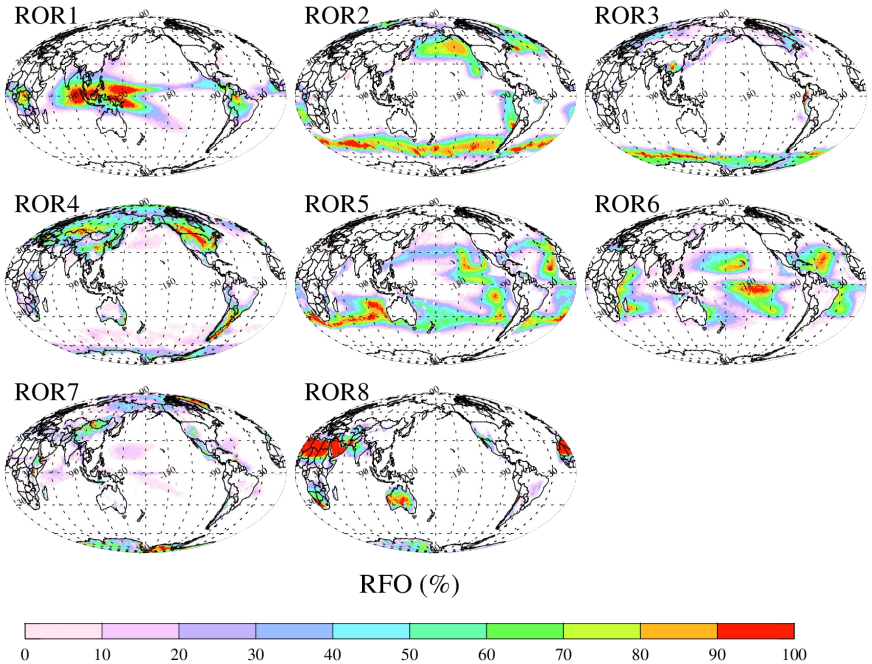


		CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9	CR10	CR11	CR12	CF
Convective lifting	ROR 1	11.8	13.8	4.4	13.3	2.4	3.3	0.8	0.1	1.1	7.8	39.7	1.6	59.1
Middle latitude oceanic storms	ROR 2	0.5	0.3	5.5	5.3	9.6	7.1	9.2	10.9	15.6	15.9	18.9	1.2	69.7
High latitude midlevel clouds	ROR 3	0.5	0.1	3.2	2.1	12.0	20.8	20.2	6.7	7.0	8.5	17.4	1.3	73.0
Continental high latitude and polar environment	ROR 4	0.4	0.2	2.9	4.1	8.2	12.9	6.8	5.3	4.8	5.0	42.0	7.4	54.1
Low marine cloud environment	ROR 5	0.9	1.7	3.1	6.4	3.5	3.0	6.7	1.8	7.8	31.0	32.2	2.1	55.4
Subtropical convection and low cloud environment	ROR 6	1.3	3.3	1.7	5.6	1.8	1.9	2.2	0.4	2.2	23.8	52.8	3.1	44.5
Suppressed fair-weather	ROR 7	0.5	0.9	0.7	2.4	3.1	6.5	1.5	1.8	1.1	2.3	66.0	13.3	35.2
Arid environment	ROR 8	0.1	0.6	0.6	2.3	1.7	2.7	0.7	0.2	0.4	1.4	35.1	54.1	18.4

Seasonal geographical distribution of RORs



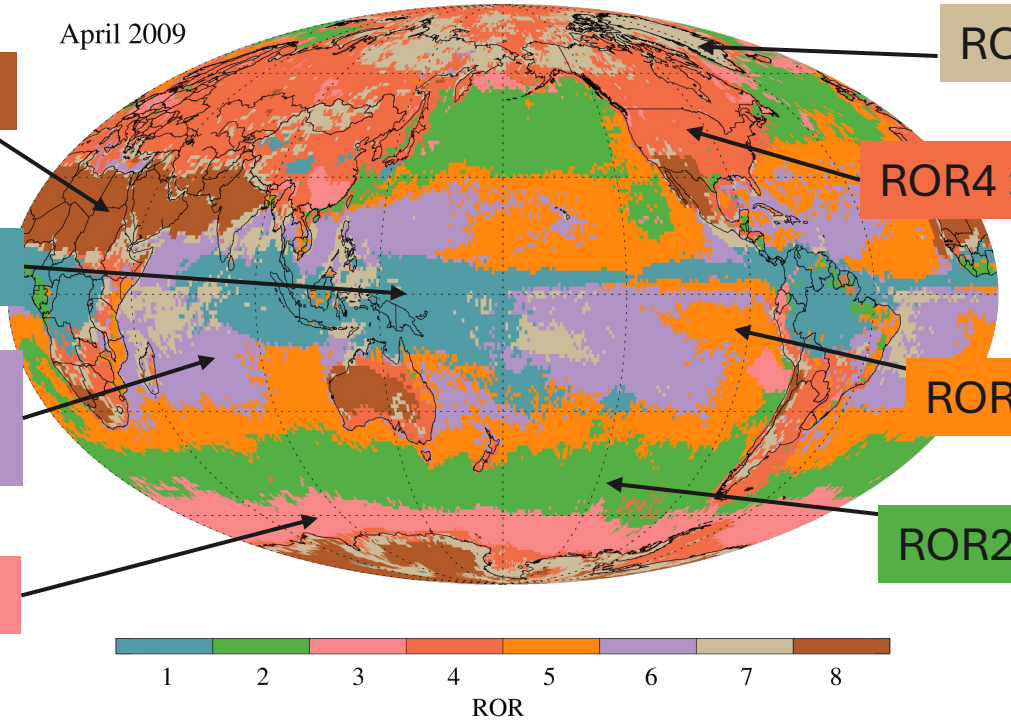
Multi-annual relative frequency of occurrences



How do we define the cloud systems?

Monthly cloud systems : Regimes Of Regimes (ROR)

Seasonal geographical distribution of RORs



ROR8 : arid almost clear

ROR1 : tropical convective

ROR6 : subtropical shallow convection

ROR3: high-lat thick stratus

ROR7 : suppressed low CF

ROR4 : mid-lat continental mid-level

ROR5 : subtropical shallow marine

ROR2 : mid-lat oceanic storm track

15 FEBRUARY 2025 CHO ET AL.

Describing Seasonal Mixtures of Cloud Regimes via "Regimes of Regimes"

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- ✓ CloudSat/CALIPSO Cloud type
- ✓ Cloud vertical structure
- ✓ Cloud precipitation radar Reflectivities
- ✓ Cloud radiative effect (CRE), CRE trends, CRE feedback