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A review of CO_2-equivalent metrics for surface albedo change in land management contexts

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CIRAD & CLAND virtual workshop on "Albedo & Climate Change Mitigation", December 3-4, 2020

Why "CO_2-equivalence"?

- A **common currency** relied on in:
  - National emission inventory reporting
  - International climate agreements and emissions trading schemes
  - Integrated assessment models
  - Life-cycle (impact) assessment methodology

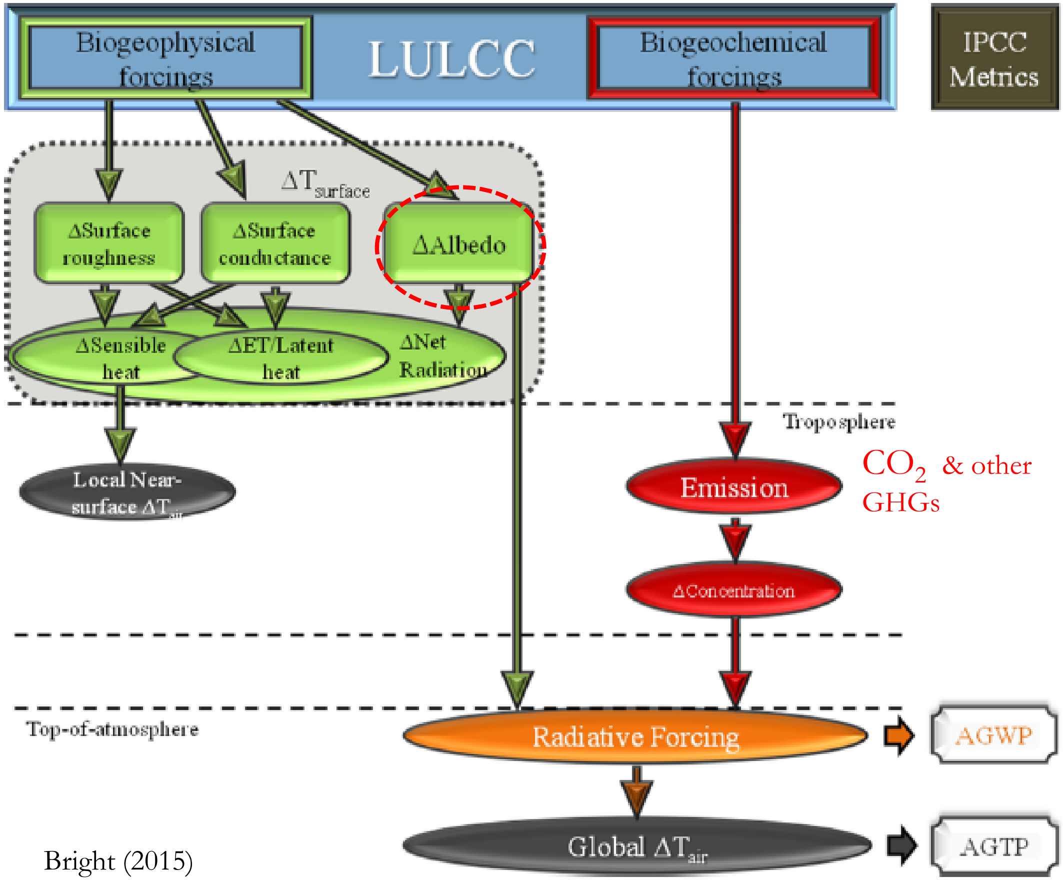
- More intuitive than "Radiative forcing" ($W\ m^{-2}$) for land resource managers and non-climate scientists

What is "equivalent"?

- Where to measure "CO_2-equivalence" on the cause-effect chain?
  - Global *Radiative Forcing* (*RF*)?
  - Global *⊿T*?
  - Local *RF* or *⊿T*?

} IPCC metrics

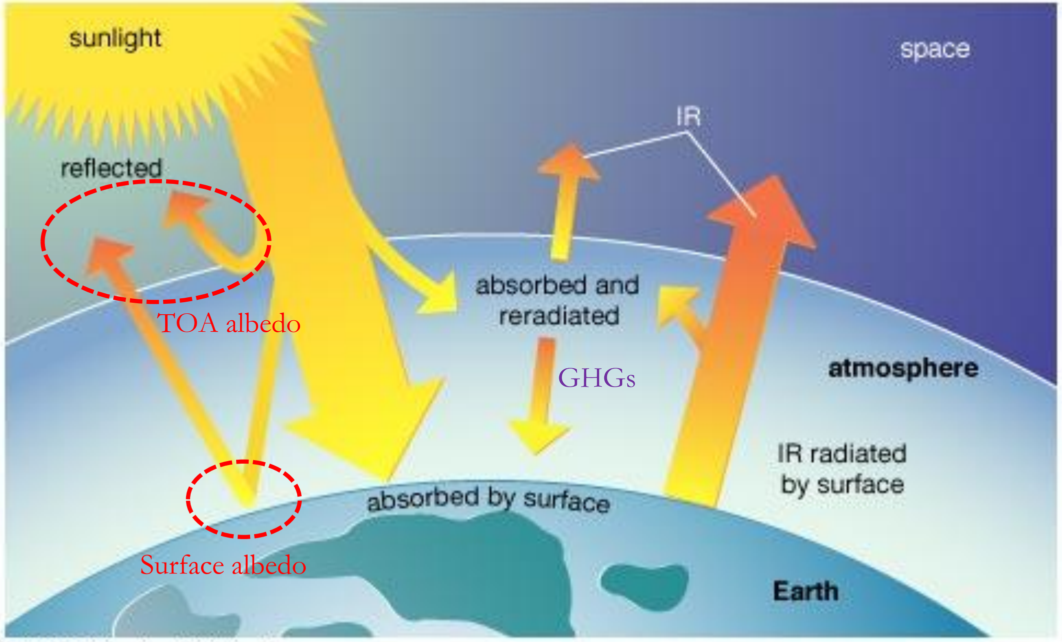
- Moving further down the cause→effect chain **increases**:
  - Policy-relevance
  - Uncertainty



Bright (2015)

What is "Radiative Forcing" (*RF*)?

- *RF* = Any **change** to Earth's **net radiative energy balance** relative to some reference state
- Net energy balance = Absorbed solar radiation – emitted IR (infrared) radiation
- Albedo at the **surface** affects the albedo at the **top-of-atmosphere** (TOA) and thus the amount of **solar energy absorbed by Earth**



Relevance of the "Radiative Forcing" concept

- ***RF*** vs. ***ΔT*** as the basis of "CO_2-equivalence" in ***Δalbedo*** metrics
  - *ΔT* (°C) is what we care about (particularly locally!)….

BUT…

  - *RF* is **less uncertain**
  - *RF* is **a true external forcing** of Earth's climate system
    - *ΔT* may include internal signals (atm. & ocean feedbacks)
  - *RF* is **easier to compute**
    - Does not require a coupled climate model

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CO2-equivalence metrics for surface albedo change based on the radiative forcing concept: A critical review

Ryan M. Bright and Marianne T. Lund

- A review of 27 studies spanning 20 years
- Questions in scope:
    - What metrics have been applied?
    - What are their (de)merits?
    - Where are future research efforts needed?

} Structure of remaining presentation

Emission equivalence of shortwave forcing ("*EESF*")

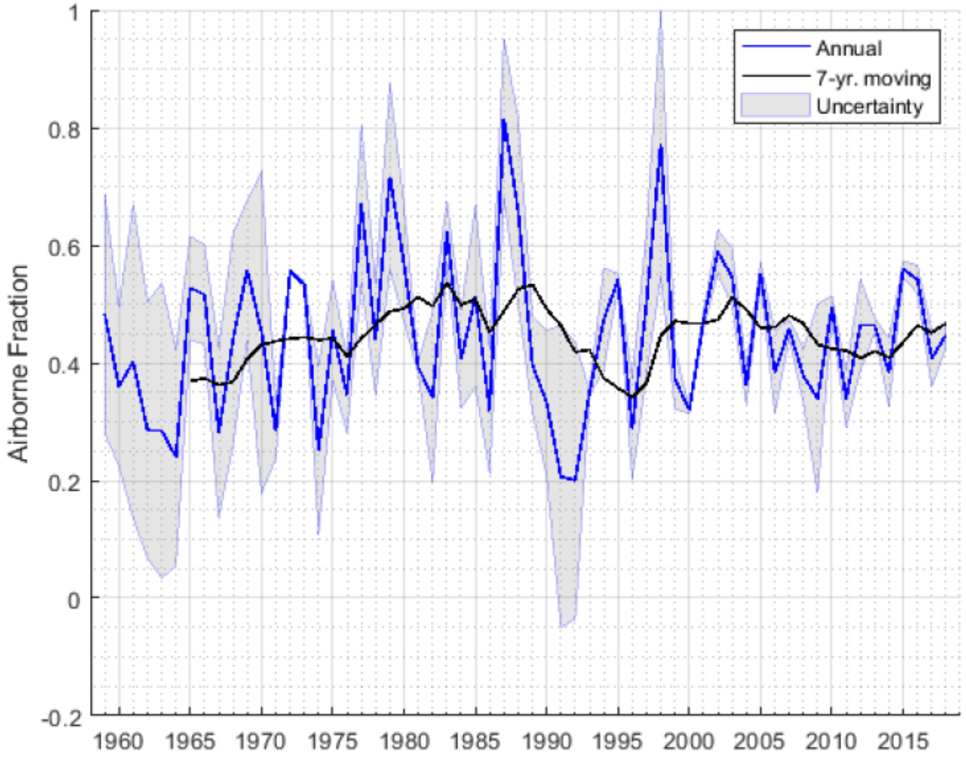
- First CO_2-eq. metric for $\Delta\alpha$ to appear in literature
- Betts (2000):
  - $$EESF = \frac{RF_{\Delta\alpha}\,[\mathrm{W\,m^{-2}}]}{k_{CO2}[\mathrm{W\,m^{-2}\,kg^{-1}}]A_E[\mathrm{m^2}]AF} \quad [\mathrm{kg\ CO_2\text{-}eq.\ m^{-2}}]$$
- Gives a single CO_2-eq. pulse emission/removal
- Assumes $\Delta\alpha$ and atmospheric CO_2 perturbations have **no time-dependency** across interannual time scales
  - Relies on the use of an "airborne fraction" (*AF*) to link CO_2 emissions with atm. concentrations

Terms:

- $RF_{\Delta\alpha}$ = Local instantaneous ΔSW at TOA
- k_{CO2} = Global mean radiative efficiency of 1 kg increase in atm. CO_2
- A_E = Earth's total surface area
- AF = Airborne fraction

Airborne fraction (“*AF*”)

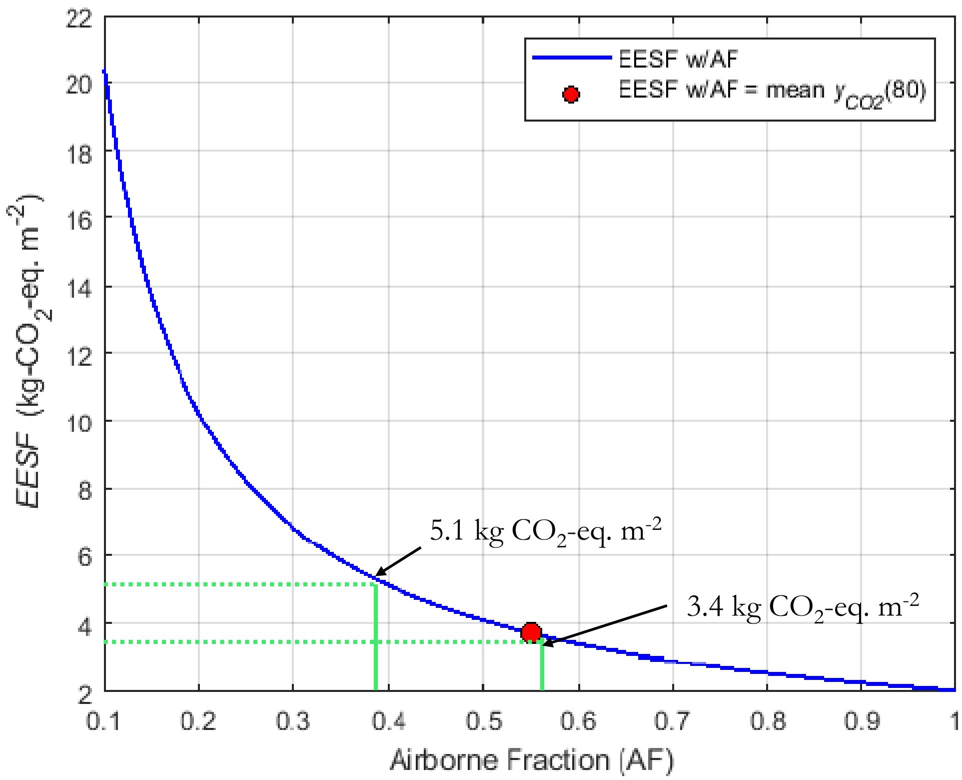
- ➢ The ratio of the annual increase in atmospheric CO_2 to the CO_2 emissions from anthropogenic sources (i.e., fossil fuels and LULCC)
- ➢ Exhibits large fluctuations across short time scales



Bright & Lund (unpublished) Data from: Friedlingstein *et al.* (2019)

EESF cont…

- The *EESF* metric is **highly sensitive** to choice of *AF*
  - Shown here for local *RF* = 1.8 W m^{-2} (corresponds to albedo difference between an 80-yr. spruce and birch forest in Norway)
- *AF* of last 7 years: 0.39 – 0.56
- Mean *AF* after 80 yrs. estimated with a CO_2 impulse-response function ("y_{CO2}") = 0.55



Bright & Lund (unpublished)

Time-dependent emissions equivalence (“*TDEE*”)

- Bright *et al.* (2016):
  - *RF(t)* from a CO_2 emission scenario: $RF_{CO2}(t) = k_{CO2} \sum_{t'=0}^{t} e_{CO2}(t') y_{CO2}(t - t')$
    - Substitute $RF_{CO2}(t)$ for $RF_{\Delta\alpha}(t)$ and solve for “$e_{CO2}(t)$”
  - $TDEE = A_E^{-1} k_{CO2}^{-1} Y_{CO2}^{-1} RF_{\Delta\alpha}^{*}$ [kg CO_2-eq. m^{-2} t^{-1}]
- *TDEE* requires the practitioner to define a time-dependent (interannual) $\Delta\alpha$ scenario *a priori*
- Gives a **time-series** of CO_2-eq. pulses

Terms:

- $RF^{*}_{\Delta\alpha}$ = $t \times$ n vector of local instantaneous $\Delta SW(t)$ at TOA
- Y_{CO2} = $t \times t$ lower triangular matrix of describing atmospheric CO_2 abundance in time following unit pulse emissions
- k_{CO2} = global mean radiative efficiency of CO_2 per 1 kg increase in atm. CO_2 concentration
- A_E = Earth’s total surface area
- t = time step (yr)

Global Warming Potential ("*GWP*")

- *GWP*, IPCC 1990s:
  - $$GWP(TH) = \frac{\sum_{t=0}^{TH} RF_{\Delta\alpha}(t)\ [\mathrm{W\ yr\ m^{-2}}]}{\sum_{t=0}^{TH} RF_{CO2,\,1\,\mathrm{kg}}(t)\ [\mathrm{W\ yr\ m^{-2}}]} \times \frac{1}{k_{CO2}[\mathrm{W\ m^{-2}\ kg^{-1}}]A_E[\mathrm{m^2}]}$$ [kg CO_2-eq. m^{-2}]

Terms:

- $RF_{\Delta\alpha}(t)$ = Local instantaneous ΔSW at TOA (from $\Delta\alpha$) at step t
- $RF_{CO2}(t)$ = Global mean net radiative flux change at tropopause (stratosphere-adjusted) at step t following a 1 kg CO_2 pulse at step $t = 0$
- k_{CO2} = global mean radiative efficiency of CO_2 per 1 kg increase in atm. CO_2 concentration
- A_E = Earth's total surface area
- TH = Metric time horizon
- t = time step (yr)

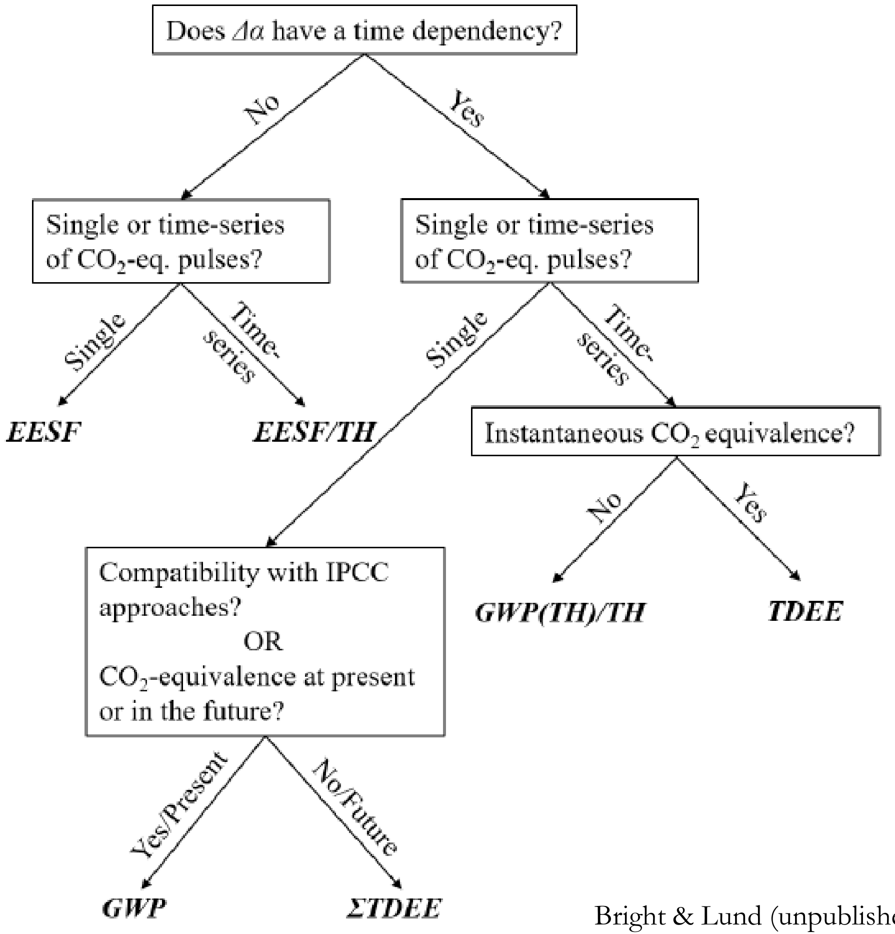
- Gives a single CO_2-eq. pulse emission/removal
- Like *TDEE*, *GWP* requires the practitioner to define a time-dependent (interannual) $\Delta\alpha$ scenario *a priori*
- Choice of *TH* is subjective

Metric permutations

- *EESF/TH*
  - Gives a uniform CO_2-eq. pulse time series, i.e., with units in **kg CO_2-eq. m^{-2} t^{-1}**
- *GWP(TH)/TH*
  - Gives a uniform CO_2-eq. pulse time series, i.e., with units in **kg CO_2-eq. m^{-2} t^{-1}**
- *ΣTDEE*
  - Gives a single CO_2-eq. pulse, i.e., with units in **kg CO_2-eq. m^{-2}**

Metric decision tree

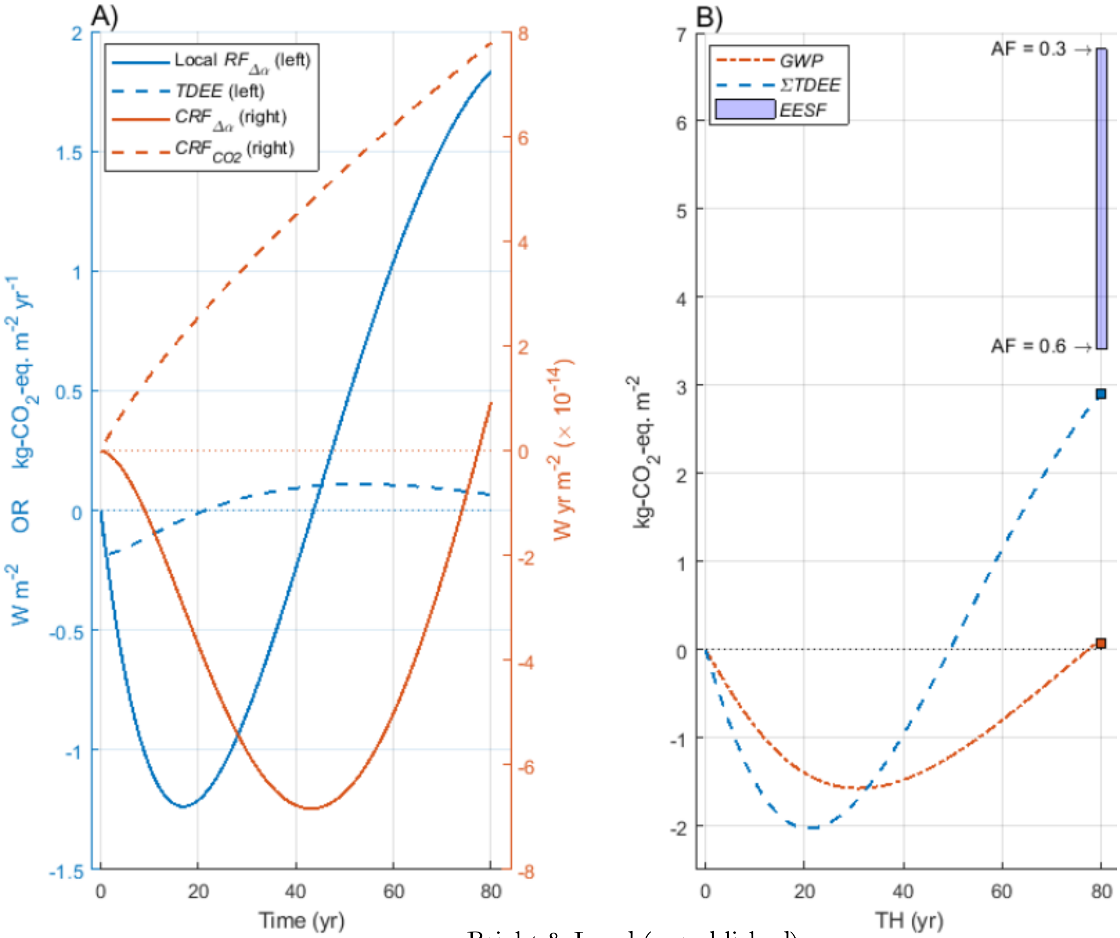
- Key metric choices:
  - Time-dependency of ⊿α and CO_2
  - Physical interpretation of "CO_2-equivalance"
- Are context specific
  - Choices may reflect:
    - Constraints on knowledge or data availability
    - Decision-support needs



Bright & Lund (unpublished)

Quantitative benchmarking: single pulse metrics

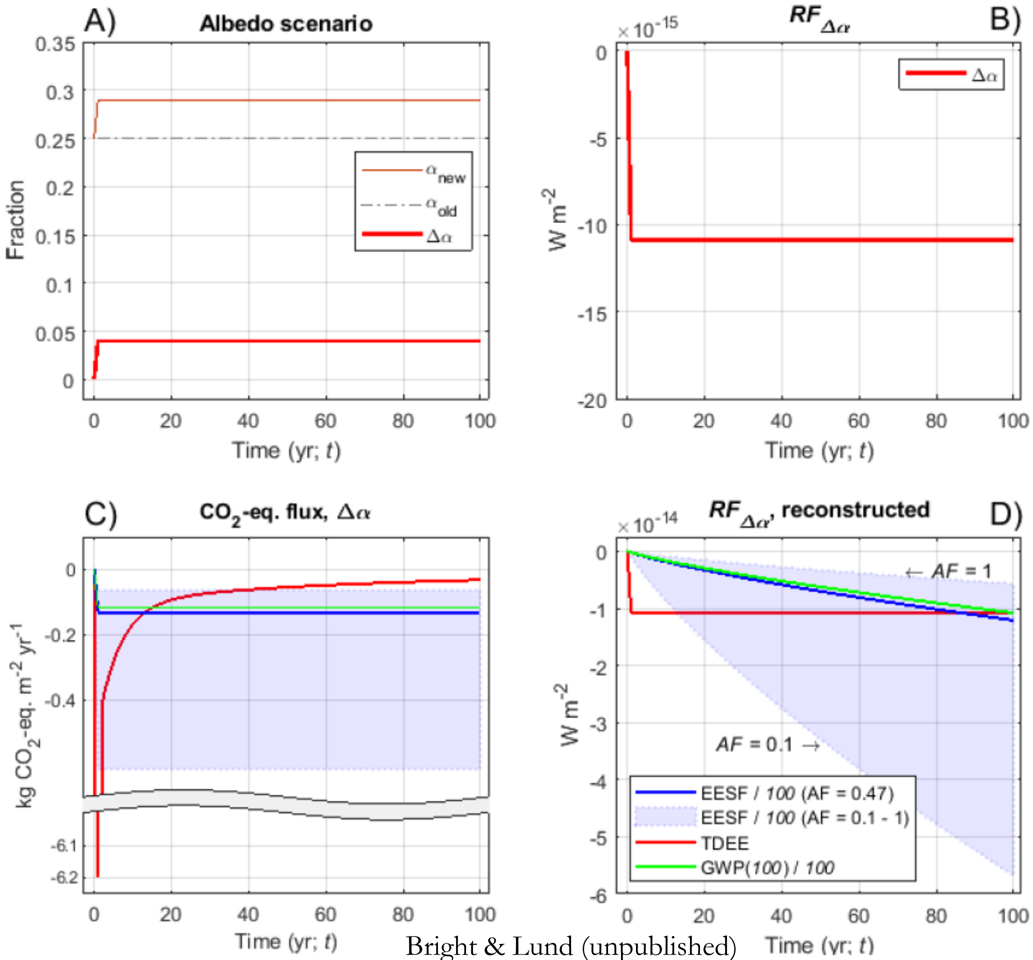
- E.g., ***GWP*** vs. ***ΣTDEE*** vs. ***EESF***
- *Δα* case: Tree species change
  - Harvest a birch forest and plant spruce
  - Evaluate at end of spruce rotation (i.e., *TH* = 80 yrs.)



Bright & Lund (unpublished)

Quantitative benchmarking: time series metrics

- E.g., ***GWP(TH)/TH*** vs. ***EESF/TH*** vs. ***TDEE***
- $\Delta\alpha$ case: Permanent albedo increase (e.g., white roofing)
  - Albedo increases in first year and remains fixed
  - Evaluate at the end of 100 years (i.e, TH = 100 yrs.)

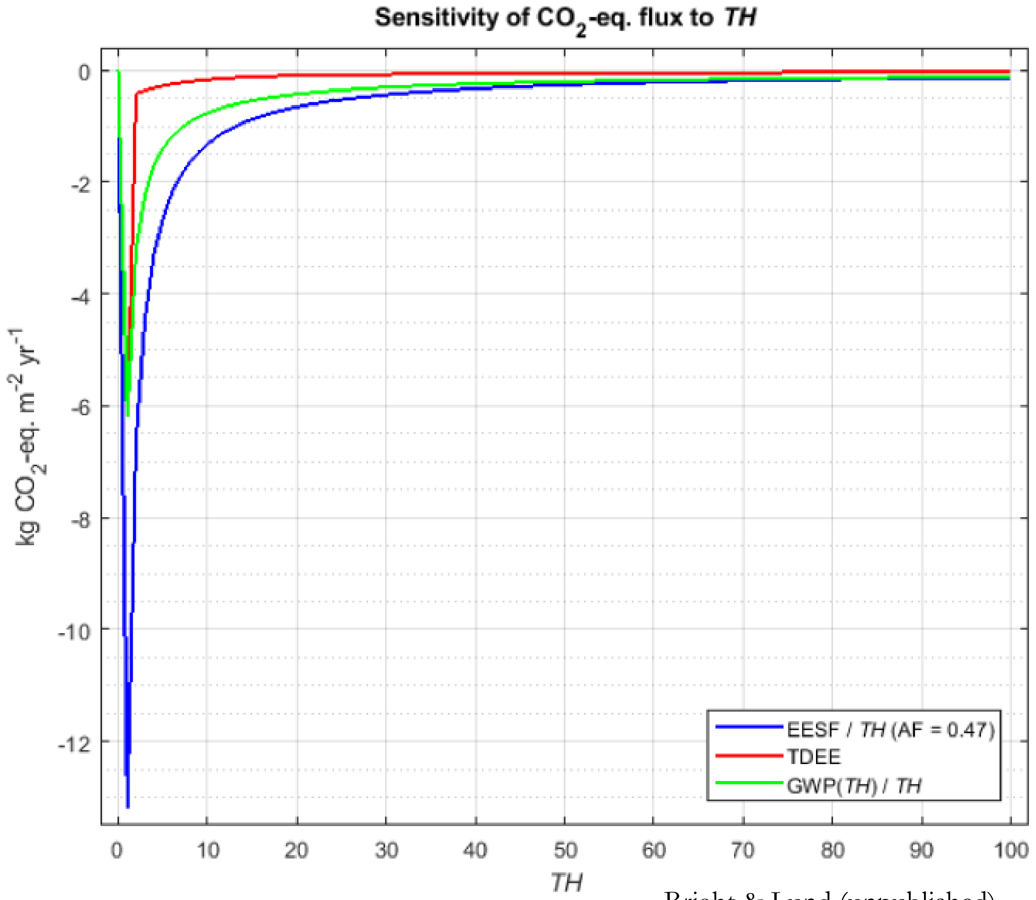


Bright & Lund (unpublished)

Note: Panels C) and D) share a legend

Sensitivity of time series metrics to *TH*

- **Increasing sensitivity** of *EESF/TH* and *GWP(TH)/TH* to **decreasing *TH***
- *TDEE* is **not a function of *TH*** and is thus insensitive to *TH*



Bright & Lund (unpublished)

Summary of review findings

- Since 2000, three *RF*-based metrics and their permutations have been applied to convert $\Delta\alpha$ in to "CO_2-equivalence"
- These differ by:
  - Whether $\Delta\alpha$ is assumed to have "lifetime" thus time-dependency (i.e., $\Delta\alpha = f(t)$)
    - YES → *TDEE*; *GWP(TH); ΣTDEE*; *GWP(TH)/TH*
    - NO → *EESF*; *EESF/TH*
  - Whether "CO_2-eq." is a scaler (single pulse) or vector (time-series of pulses)
    - Single pulse → *GWP(TH); ΣTDEE*; *EESF*
    - Pulse time-series → *TDEE*; *GWP(TH)/TH*; *EESF/TH*
  - Whether $RF_{\Delta\alpha}$ is normalized to RF_{CO2}
    - Normalized → *EESF*; *EESF/TH; GWP(TH)*; *GWP(TH)/TH*
    - Non-normalized → *TDEE*; *ΣTDEE*

Summary of review findings cont…

- Their **relative merits** are context-specific
  - Does ⊿α vary over time (interannually)?
    - *TDEE* and *GWP* **are superior** to *EESF* when applied to assess the relevance of ⊿α of dynamic systems
  - Does the decision-support context require comparision to an emission scenario or to a unit pulse emission?
    - For a scenario: *TDEE* **is superior** to *EESF/TH* and *GWP(TH)/TH*
  - Is compatibility with other frameworks (i.e., UNFCC reporting, LCA, etc.) or conformity to IPCC emission metrics needed?
    - *GWP* **over** *ΣTDEE*
  - Is compatibitility with policy targets based on cumulative emissions desired?
    - *ΣTDEE* **over** *GWP*

Summary of review findings cont…

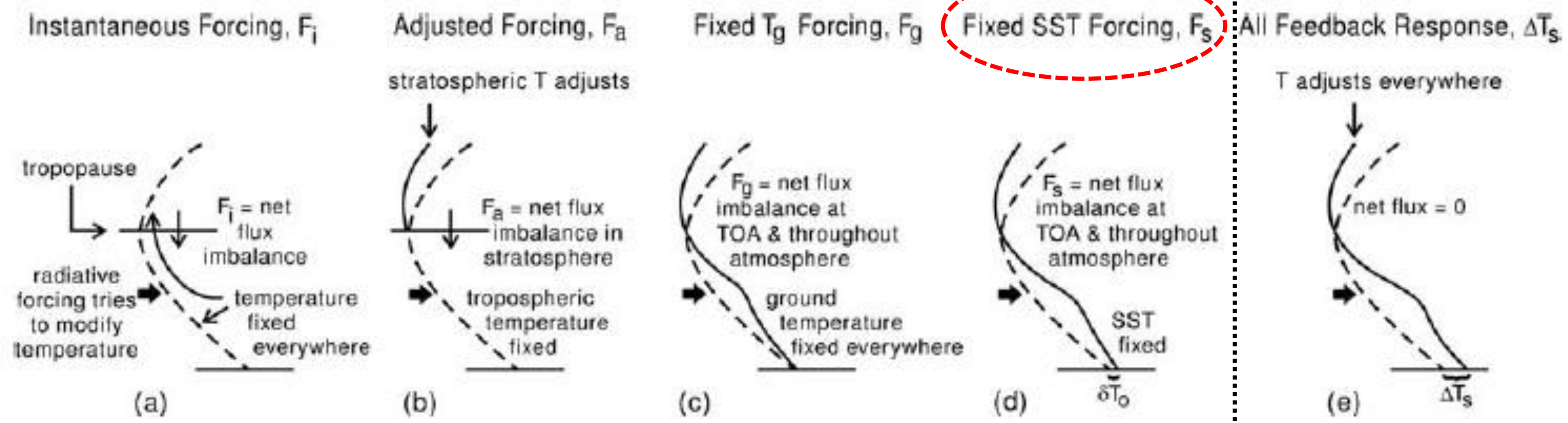
- BUT, in **absolute terms** their **merits are questionable**
  - The metrics presented today assume $RF_{\Delta\alpha}$ and RF_{CO2} are additive
  - Large disparity in climate response between $RF_{\Delta\alpha}$ and RF_{CO2}
    - $\Delta T(RF_{\Delta\alpha} + RF_{CO2}) \neq \Delta T(RF_{\Delta\alpha}) + \Delta T(RF_{CO2})$
- Two reasons for this disparity:

1. Differences in the spatial extent of the two forcings
   - Feedback patterns driving the response have a strong spatial dependency
     - CO_2 is well-mixed in Earth's atmosphere thus imposing a spatially homogeneous (extensive) forcing;
     - $\Delta\alpha$ connected to land activities is localized and typically confined to specific regions
2. Differences in radiative adjustment processes following the initial forcing
   - For CO_2, adjustments occur throughout the entire troposphere and stratosphere
   - For $\Delta\alpha$, adjustments are mostly confined to the lower troposphere

Effective Radiative Forcings (*ERF*)

Existing Metrics for Δα & WMGHGs

ERF in IPCC AR5



Less Additivity **More**

Hansen *et al.* (2005)

➢ *ERF* = net energy balance change at TOA **after all radiative adjustments in the atmosphere**

But what is the *ERF* of $\Delta\alpha$?

- All other surface properties remaining unperturbed, $\Delta\alpha$ will **also alter the surface turbulent heat fluxes** (latent and sensible heat)
  - Modifies vertical humidity and temperature profiles of the troposphere
    - Affects lapse rates, cloud physical properties, etc. → contributes to "radiative adjustments"
  - These affect Earth's radiative balance beyond the isolated instantaneous ΔSW from $\Delta\alpha$
- Example $\Delta\alpha$ case: **Rooftop brightening**
  - Increases $\Delta\alpha$ but decreases the sensible and latent heat fluxes
  - This enhances mixing layer stability & reduces mixing layer humidity, which **decreases low level cloud fraction and optical depths** (Menon et al. (2010); Millstein & Menon (2011); Jacobsen & Ten Hoeve (2012); Zhang et al. (2016))
    - These cloud adjustments results in increased $SW\downarrow$ at surface = decreased $LW\uparrow$ (increased $LW\downarrow$) at TOA
      - **"Effective" *RF* < instantaneous $\Delta SW\uparrow$ at TOA** (i.e, ERF **<** $RF_{\Delta\alpha}$)

Relevance of forcing type

- In land management contexts (LULCC), rarely is *only* the surface albedo perturbed
  - **Other physical properties of the surface** are often perturbed alongside *Δalbedo*

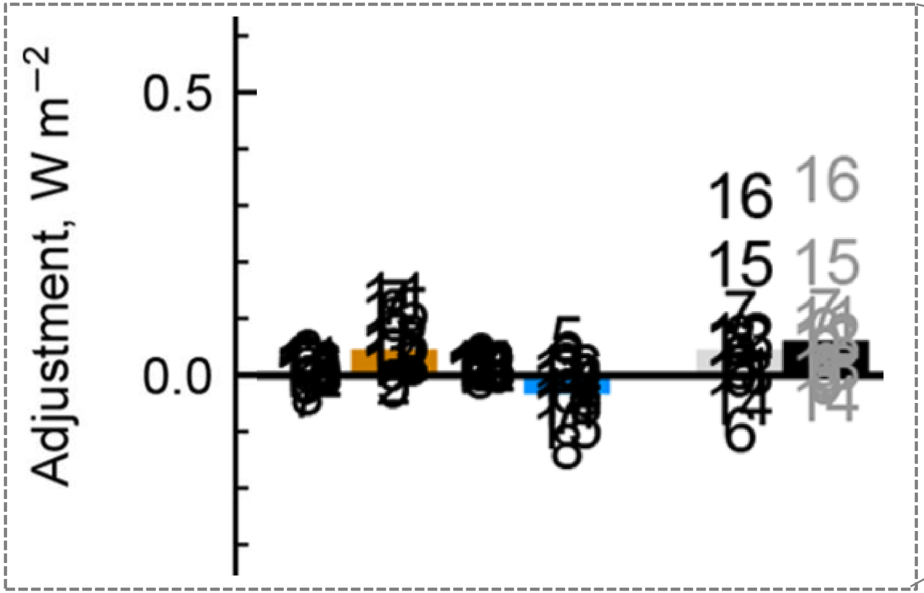
Forcing type	Surface property perturbation	Flux perturbation
Geoengineering (e.g., white roofing)	ΔAlbedo	$\Delta\lambda(E)$; ΔH
LULCC (e.g, re-/deforestation, crop change)	ΔAlbedo; ΔAerodynamic conductance; ΔSurface conductance	$\Delta\lambda(E+T)$; ΔH

1850-2014 LULCC (CMIP6 RFMIP)

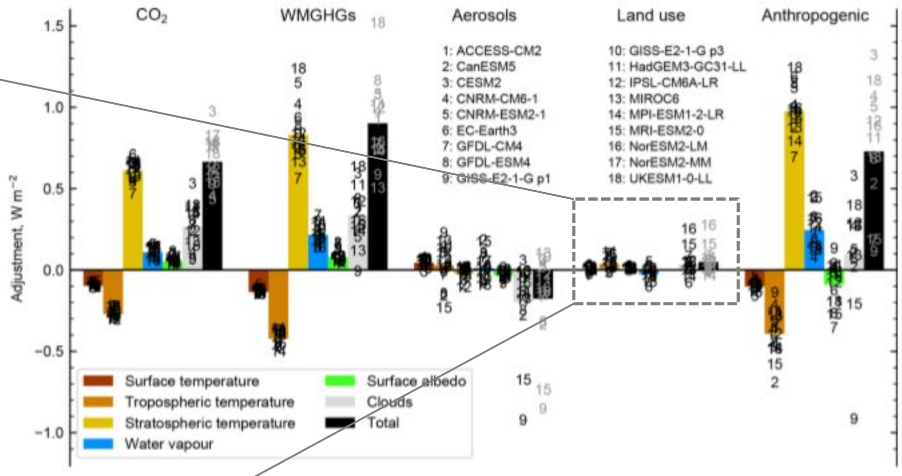
Model	ERF	IRF ($=RF_{\Delta\alpha}$)
CanESM5	−0.08	−0.10
CESM2	−0.04	−0.08
CNRM-ESM2-1	−0.07	−0.08
GFDL-CM4	−0.33	−0.42
GISS-E2-1-G	−0.00	0.02
HadGEM3-GC31-LL	−0.11	−0.16
IPSL-CM6A-LR	−0.05	−0.11
MIROC6	−0.03	−0.10
MPI-ESM1-2-LR	−0.10	−0.01
MRI-ESM2-0	−0.17	−0.33
NorESM2-LM	0.26	−0.01
UKESM1-0-LL	−0.30	−0.28
Mean	−0.08	−0.14
St. dev.	0.14	0.13

Smith *et al.* (2020)

Radiative adjustments of LULCC (1850-2014; CMIP6 RFMIP)



Smith *et al.* (2020)



- Positive "Tropospheric temperature" & "Cloud" adjustments dominate which are partly offset by "Water vapor" adjustments
- **BUT** – highly uncertain!

Implications for $\Delta\alpha$ metrics

- Using ERF_{LULCC} over $RF_{\Delta\alpha}$ in the metric calculation would help overcome the response disparity (or "additivity") issue of CO_2-eq. metrics based on the *RF* concept…
- ….but this strays away from metric principles! Metrics should:
  - Be **transparent and easy to compute**
  - Have **low uncertainty**
- *ERF* requires a climate model
  - Climate models differ in their underlying representations of key physical processes
  - *ERF* is also **sensitive to the spatial scale, pattern, and type** of LULCC that is imposed in the climate model

What about radiative forcing "efficacies"?

- Efficacy of LULCC forcing type "*x*" – or $E_x = \lambda_x / \lambda_{CO2}$
  - where λ is either a transient or equilibrium climate sensitivity [in °C $(W\ m^{-2})^{-1}$]
  - "*x*" = crop change, tree species change, de-/reforestation, addition of irrigation, etc.
- Same challenges as for *ERF* regarding the need to reduce uncertainties
  - BUT: **Metric practitioners could retain the focus on reducing uncertainty of $\boldsymbol{RF_{\Delta\alpha}}$**
- Example:

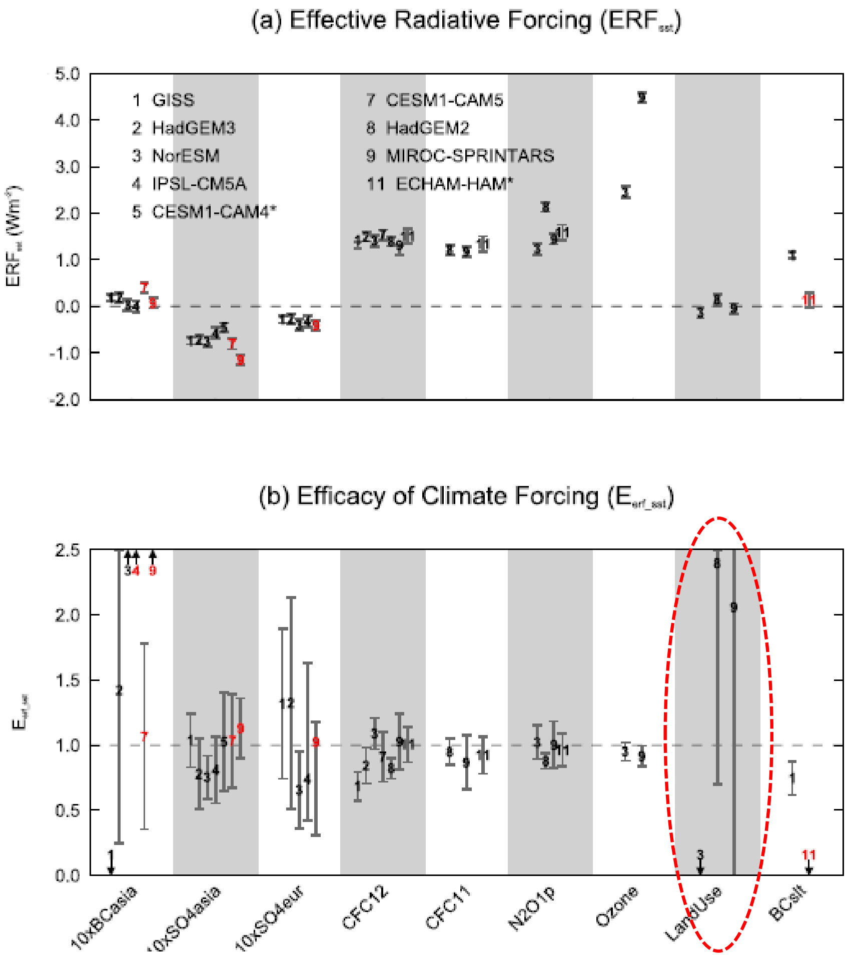
Let the climate modeling community work on reducing the uncertainties of "E_x"!

$$EESF = \frac{E_x RF_{x\ \Delta\alpha}}{k_{CO2} A_E AF}$$

Metric practitioners to maintain the focus on reducing uncertainty of estimates of instantaneous ΔSW *at TOA* from $\Delta\alpha$ connected to forcing type "*x*"

Way forward

- For the climate modeling community, **much work remains in the way of reducing uncertainties of efficacies!**
- Efforts are needed to establish consensus on climate forcing "efficacies" for a wide range of LULCC forcing types
  - Should be mindful of their sensitivity to the spatial scale, pattern, and extent to which LULCC is imposed in models



Richardson *et al.* (2019)

Vision

- A similar table but with columns representing different LULCC forcing types

$$EESF = \frac{E_x RF_{x\,\Delta\alpha}}{k_{CO2} A_E AF}$$

Table 1

PDRMIP Multimodel Mean Radiative Forcing (See section 2.3 for Definitions), GSAT Response, Climate Feedback Parameter Calculated Using First 20 years (α_20), Final 80 years (α_80), and Full 100 years (α) of Simulations, and Efficacies (See section 2.4 for Definitions) for the Five Core Experiments

	2×CO2	3×CH4	2%SOL	5×SO4	10×BC
IRF_{trop} (W m^{-2})	4.45 ± 0.11	1.04 ± 0.09	—	—	—
IRF_{toa} (W m^{-2})	2.20 ± 0.22	1.13 ± 0.13	4.81 ± 0.05	−1.73 ± 1.02	2.17 ± 1.08
RF_{strat} (W m^{-2})	3.76 ± 0.27	1.21 ± 0.28	4.55 ± 0.06	−3.64 ± 1.20	2.29 ± 1.15
ERF_{sst} (W m^{-2})	3.71 ± 0.30	1.15 ± 0.25	4.17 ± 0.13	−3.71 ± 1.94	1.18 ± 0.75
ERF_{ssta} (W m^{-2})	4.19 ± 0.35	1.25 ± 0.31	4.32 ± 0.12	−3.78 ± 1.99	1.25 ± 0.80
ERF_{reg} (W m^{-2})	3.81 ± 0.57	1.06 ± 0.25	3.89 ± 0.29	−3.70 ± 1.79	0.83 ± 0.53
ΔT (K)	2.44 ± 0.75	0.67 ± 0.33	2.46 ± 0.97	−2.45 ± 1.85	0.74 ± 0.54
α (W m^{-2}/K)	−1.19 ± 0.50	−1.06 ± 0.53	−1.24 ± 0.51	−1.11 ± 0.34	−0.89 ± 0.46
α_20 (W m^{-2}/K)	−1.27 ± 0.52	−1.28 ± 0.57	−1.36 ± 0.51	−1.51 ± 0.85	−0.97 ± 0.77
α_80 (W m^{-2}/K)	−1.03 ± 0.57	−0.93 ± 0.73	−1.04 ± 0.51	−0.80 ± 0.36	−0.78 ± 0.60
$\Delta T/IRF_{trop}$ (K/W m^{-2})	0.55 ± 0.19	0.61 ± 0.33	—	—	—
$\Delta T/IRF_{toa}$ (K/W m^{-2})	1.14 ± 0.44	0.57 ± 0.35	0.52 ± 0.21	1.25 ± 0.81	0.25 ± 0.21
$\Delta T/RF_{strat}$ (K/W m^{-2})	0.66 ± 0.24	0.57 ± 0.29	0.54 ± 0.21	0.66 ± 0.25	0.40 ± 0.25
$\Delta T/ERF_{sst}$ (K/W m^{-2})	0.67 ± 0.22	0.58 ± 0.23	0.59 ± 0.23	0.62 ± 0.19	0.63 ± 0.37
$\Delta T/ERF_{ssta}$ (K/W m^{-2})	0.59 ± 0.19	0.54 ± 0.22	0.57 ± 0.22	0.61 ± 0.18	0.60 ± 0.34
$\Delta T/ERF_{reg}$ (K/W m^{-2})	0.66 ± 0.25	0.66 ± 0.32	0.63 ± 0.25	0.63 ± 0.22	1.22 ± 1.45
E_{irf_trop}		1.09 ± 0.35	0.89 ± 0.09	2.97 ± 1.86	0.54 ± 0.29
E_{irf_toa}	—	0.48 ± 0.17	0.44 ± 0.04	1.50 ± 0.99	0.27 ± 0.13
E_{rf_strat}	—	0.84 ± 0.21	0.81 ± 0.06	0.99 ± 0.09	0.55 ± 0.16
E_{erf_sst}	—	0.87 ± 0.15	0.87 ± 0.07	0.94 ± 0.16	0.87 ± 0.31
E_{erf_ssta}	—	0.91 ± 0.18	0.95 ± 0.07	1.04 ± 0.16	0.93 ± 0.32
E_{erf_reg}	—	0.97 ± 0.23	0.96 ± 0.09	0.95 ± 0.25	1.48 ± 1.09
E_{α}	—	1.22 ± 0.47	0.97 ± 0.12	1.01 ± 0.29	1.36 ± 0.26

Note. Uncertainty bounds are the standard deviation of the intermodel spread.

Richardson *et al.* (2019)

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