Cloud Radiative Effects in “Clear Sky”: From spectral high-resolution radiance to broadband fluxes.

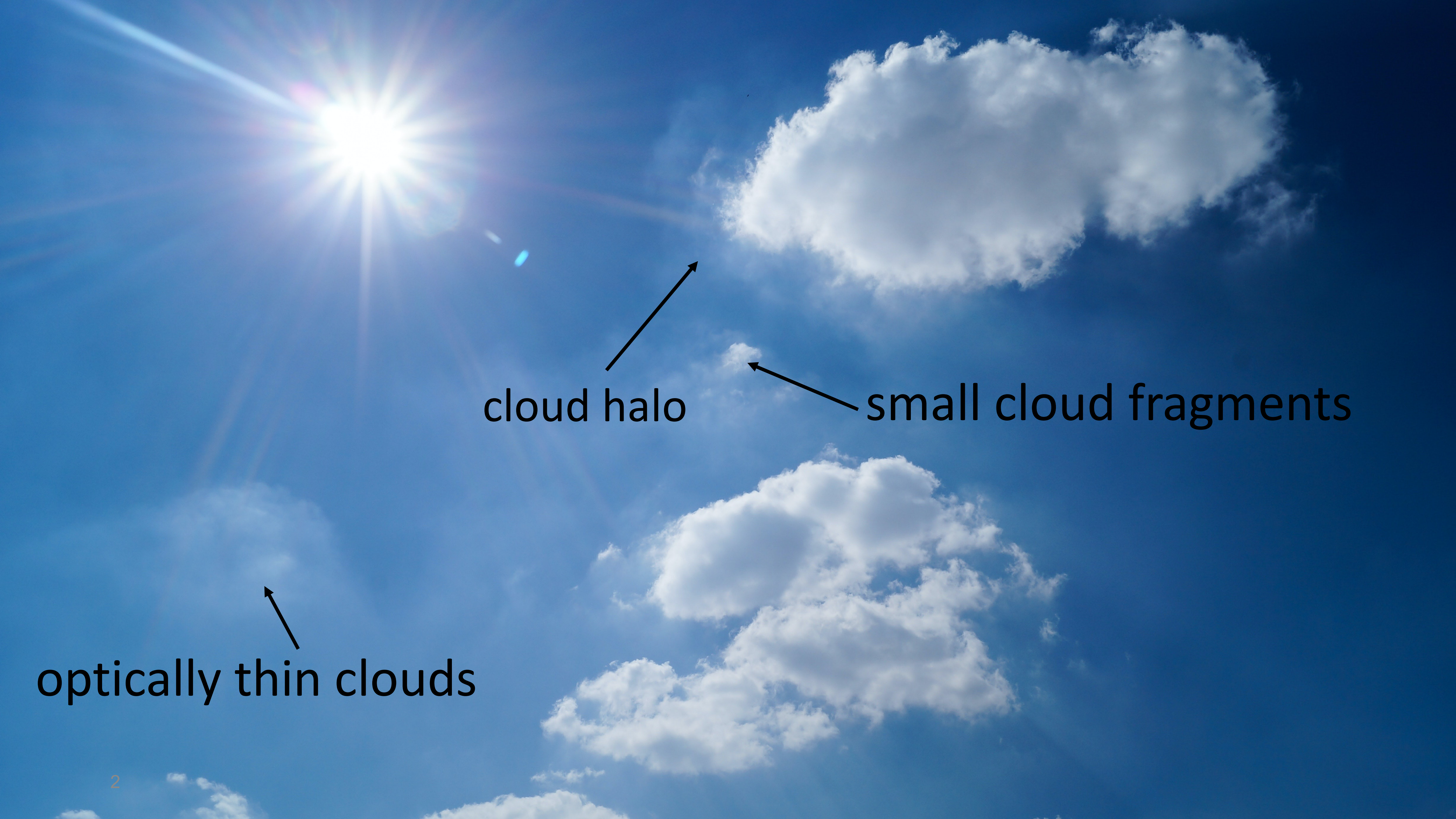
Eshkol Eytan, Jake Gristey and Graham Feingold

CIRES

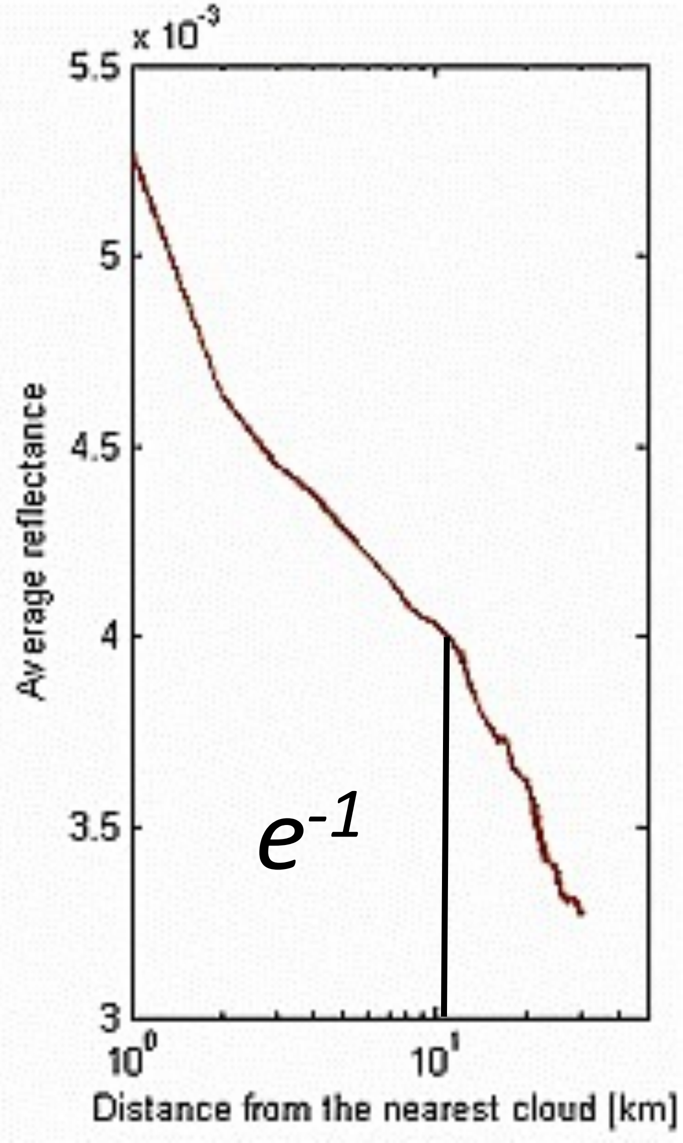
University of Colorado Boulder

NOAA

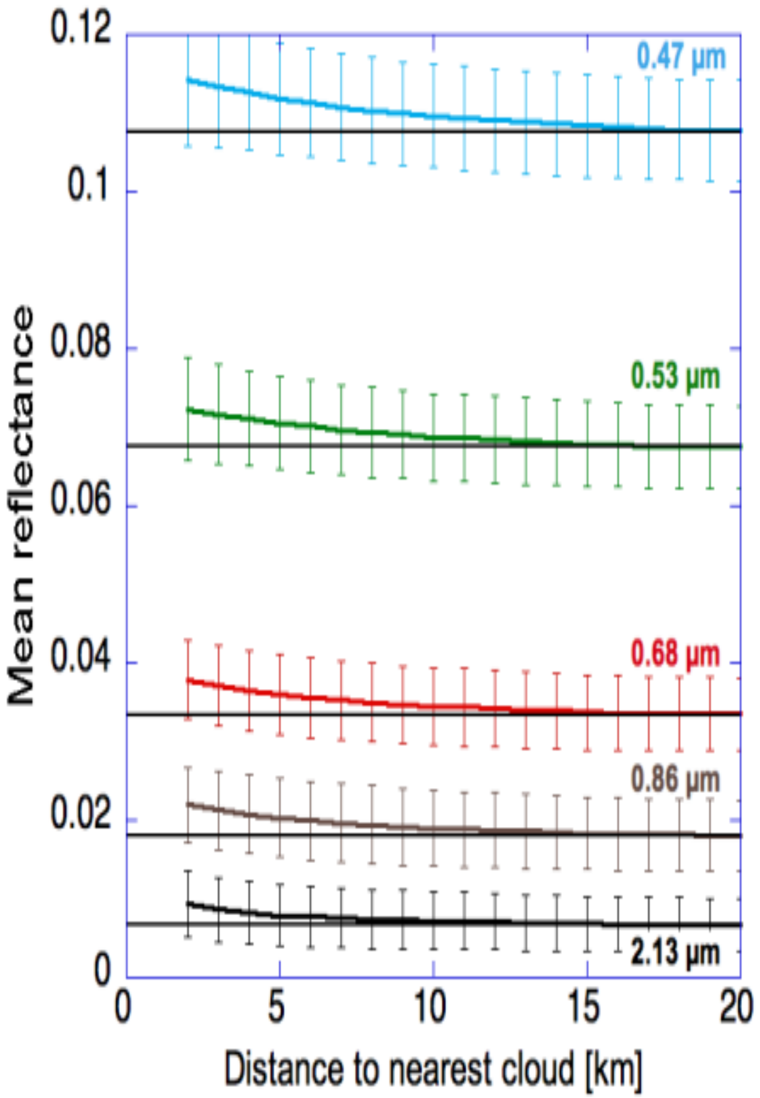
CERES spring meeting, May 2024


cloud halo
small cloud fragments
optically thin clouds

Increased reflectance near clouds

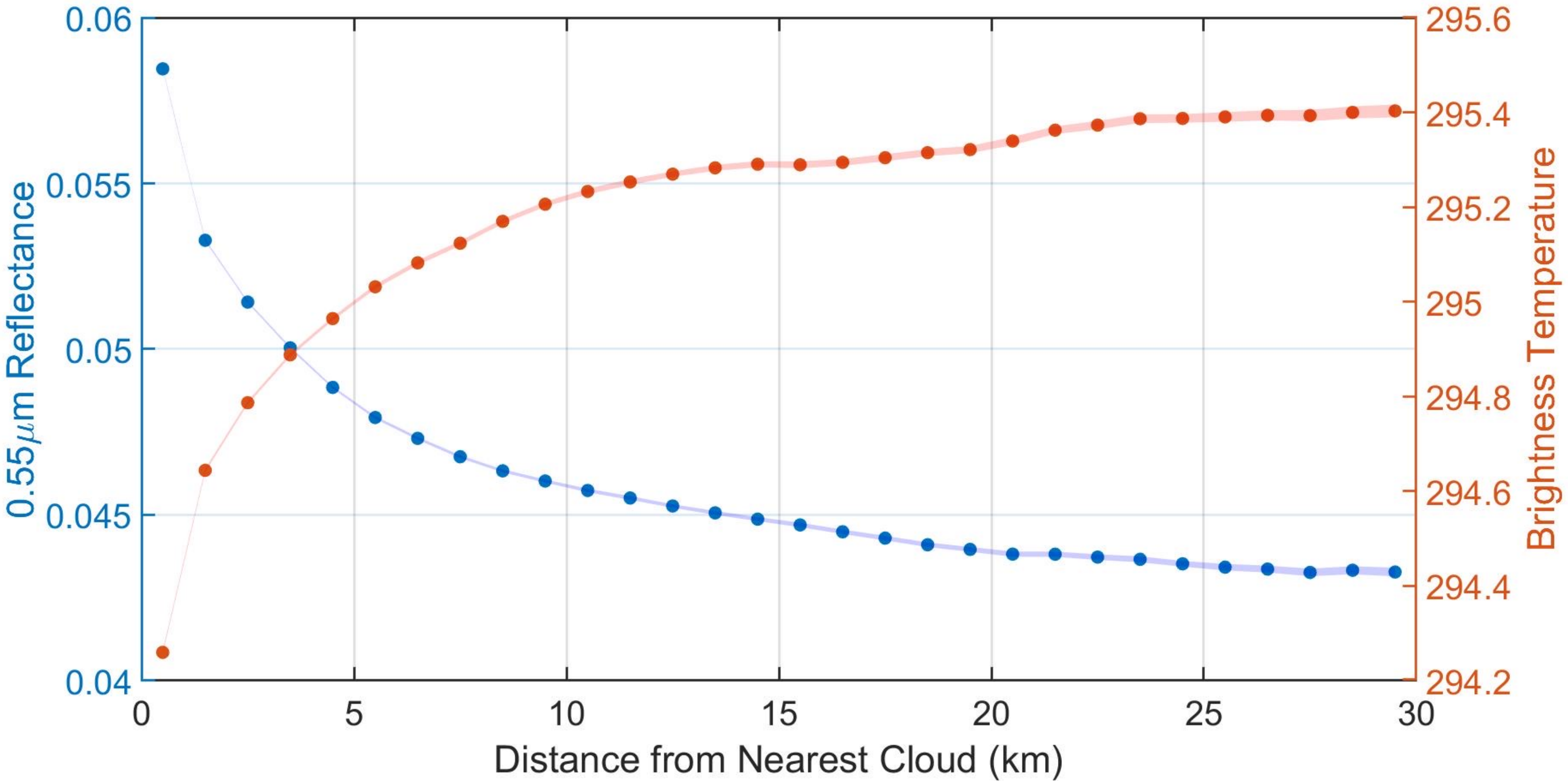


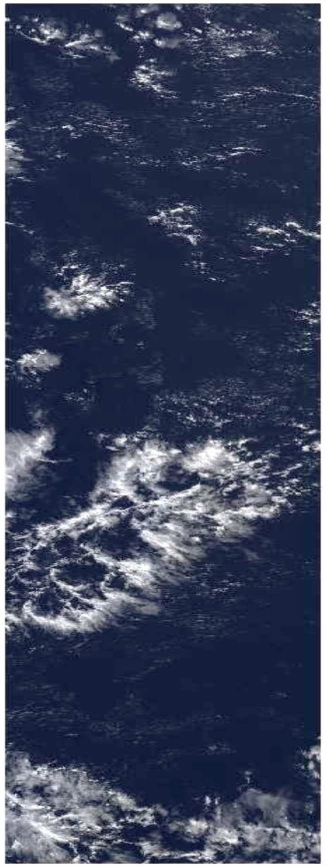
Koren et al., 2007



Varnai and Marshak 2009

The longwave twilight signal





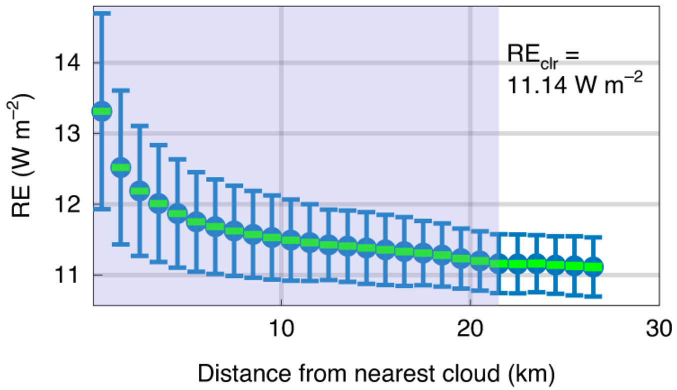
Eytan et al., 2020

The Cloud Twilight Zone is likely to be important for Earth's energy budget

- The longwave analysis suggests that undetected clouds have a large contribution to the 'Cloud Twilight Zone' .

- A lower bound for the LW twilight radiative effect is ~0.75 W/m^2.

- Its fraction of the "clear-sky" is 60%.



Eytan et al., 2020

The Cloud Twilight Zone is likely to be important for Earth's energy budget

Only a few other studies had investigated the Cloud Twilight Zone role on the radiation budget:

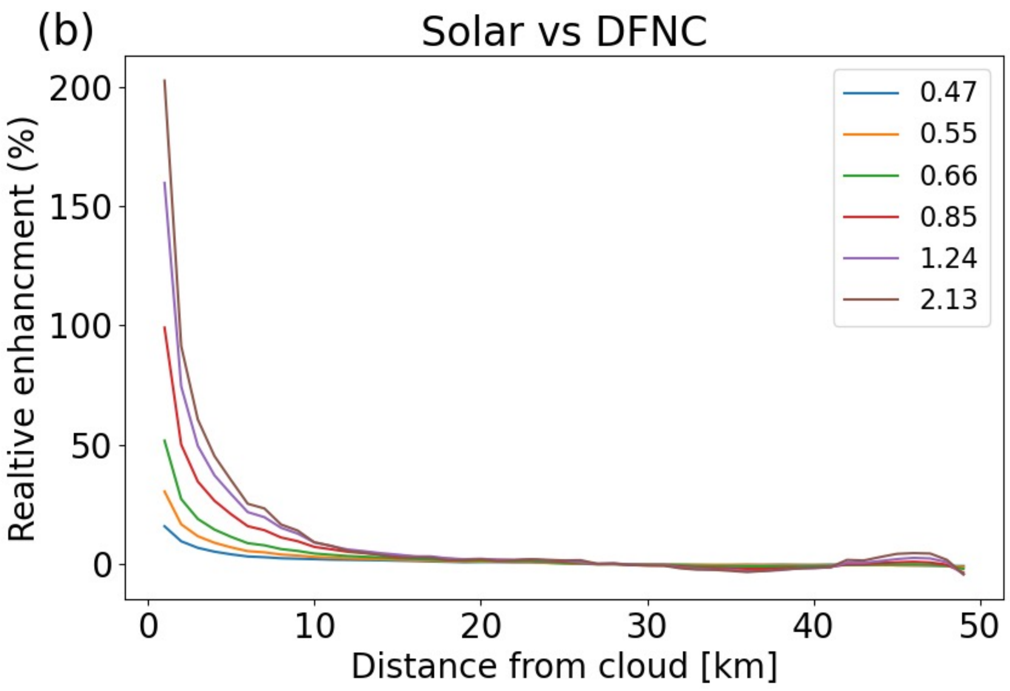
- Jahani et al., 2022 found an RE_{LW} of ~0.8 W/m^2 for warm clouds and ~8 W/m^2 for all clouds.
- Sun et al. 2011: RE_{SW} for subvisible clouds of 2.5 W/m^2

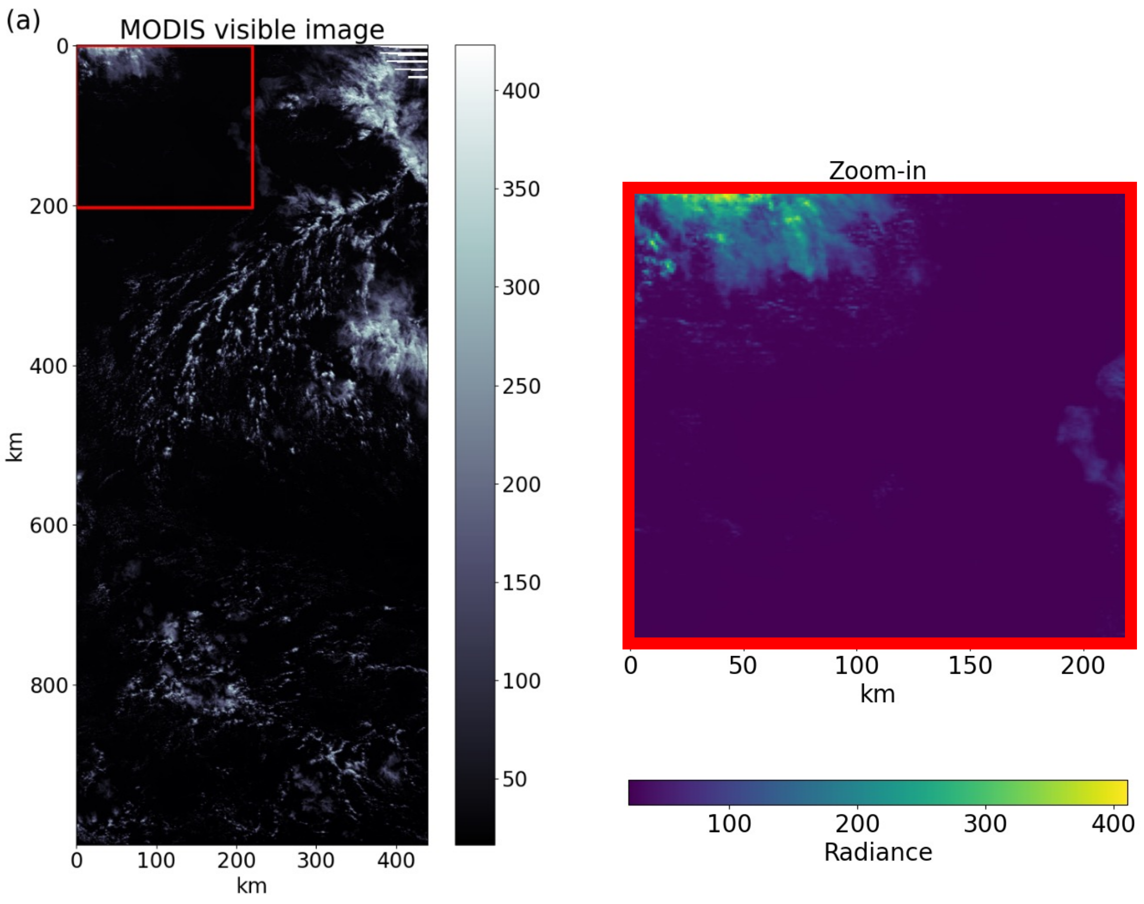
Here we estimate the radiative effect of the Cloud Twilight Zone with an observationally based approach for both LW and SW using a MODIS-CERES synergy.

Defining **PURE** clear-sky

- Break down MODIS images into small domains of 200x200 km^2.
- Take the distance from cloud profile of each wavelength.
- Construct the **Pure** clear sky spectral distribution ($I_{clr}{}^{\lambda}$).

Solar

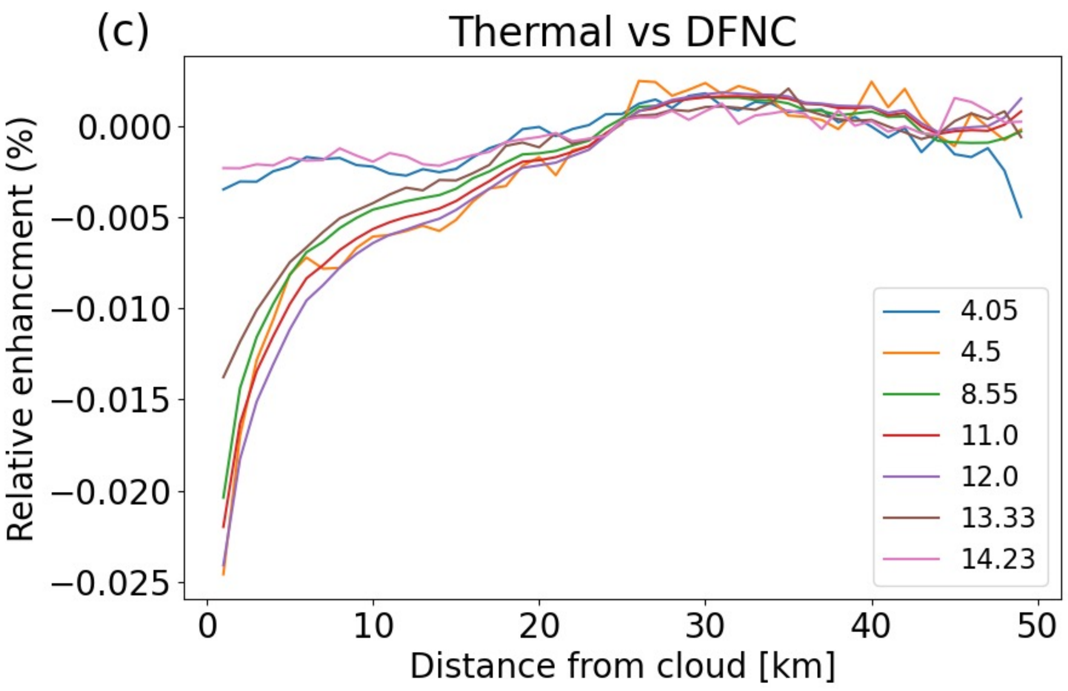


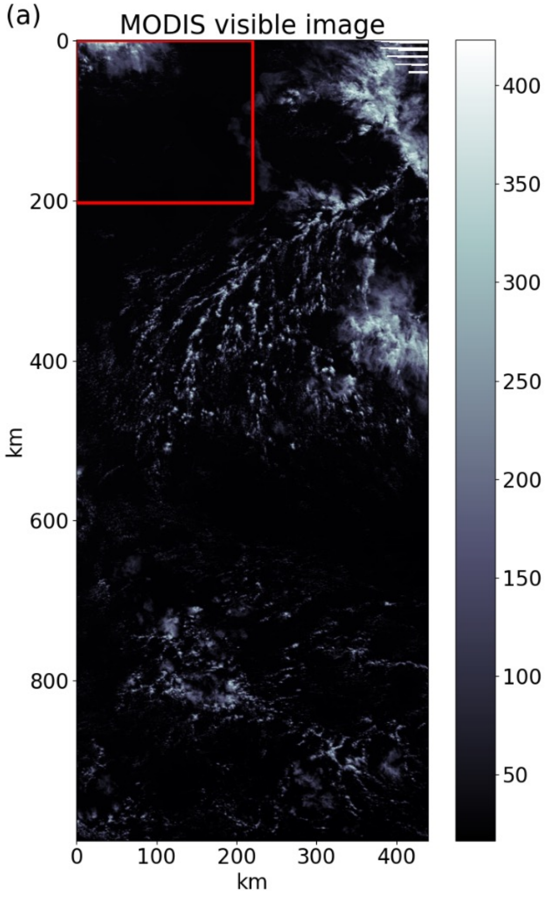


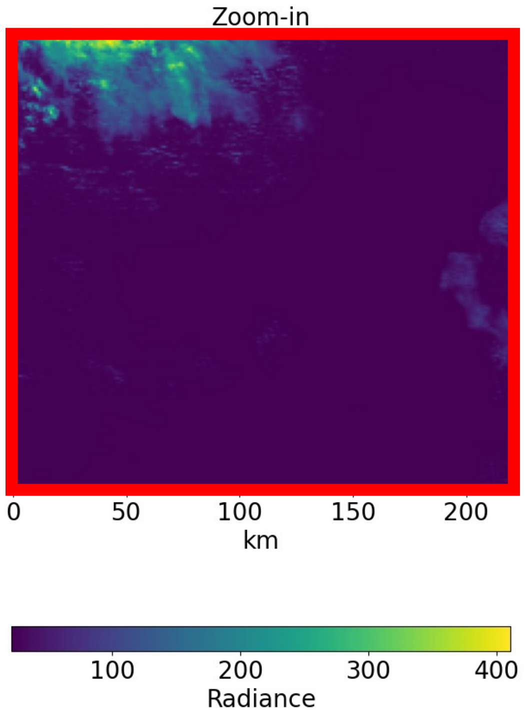
Defining **PURE** clear-sky

- Break down MODIS images into small domains of 200x200 km^2.
- Take the distance from cloud profile of each wavelength.
- Construct the **Pure** clear sky spectral distribution ($I_{clr}{}^{\lambda}$).

Thermal

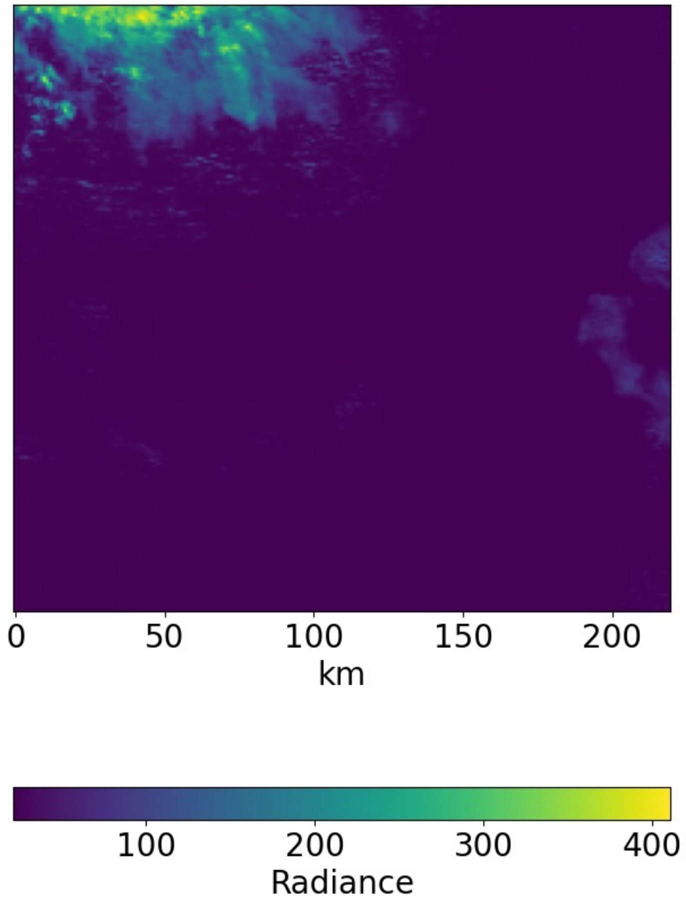


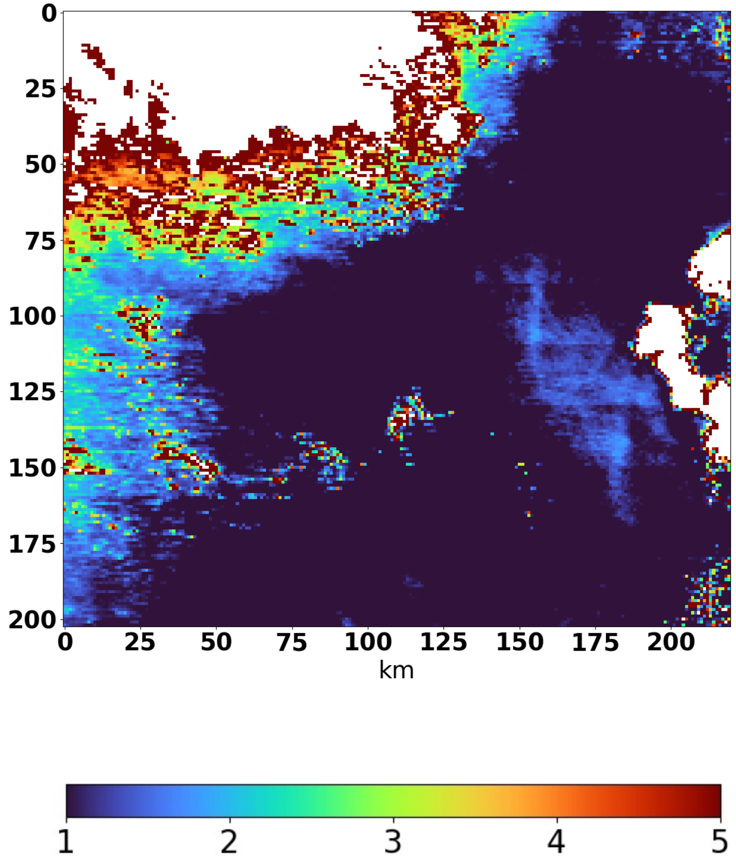




Defining **PURE** clear-sky

Visible image

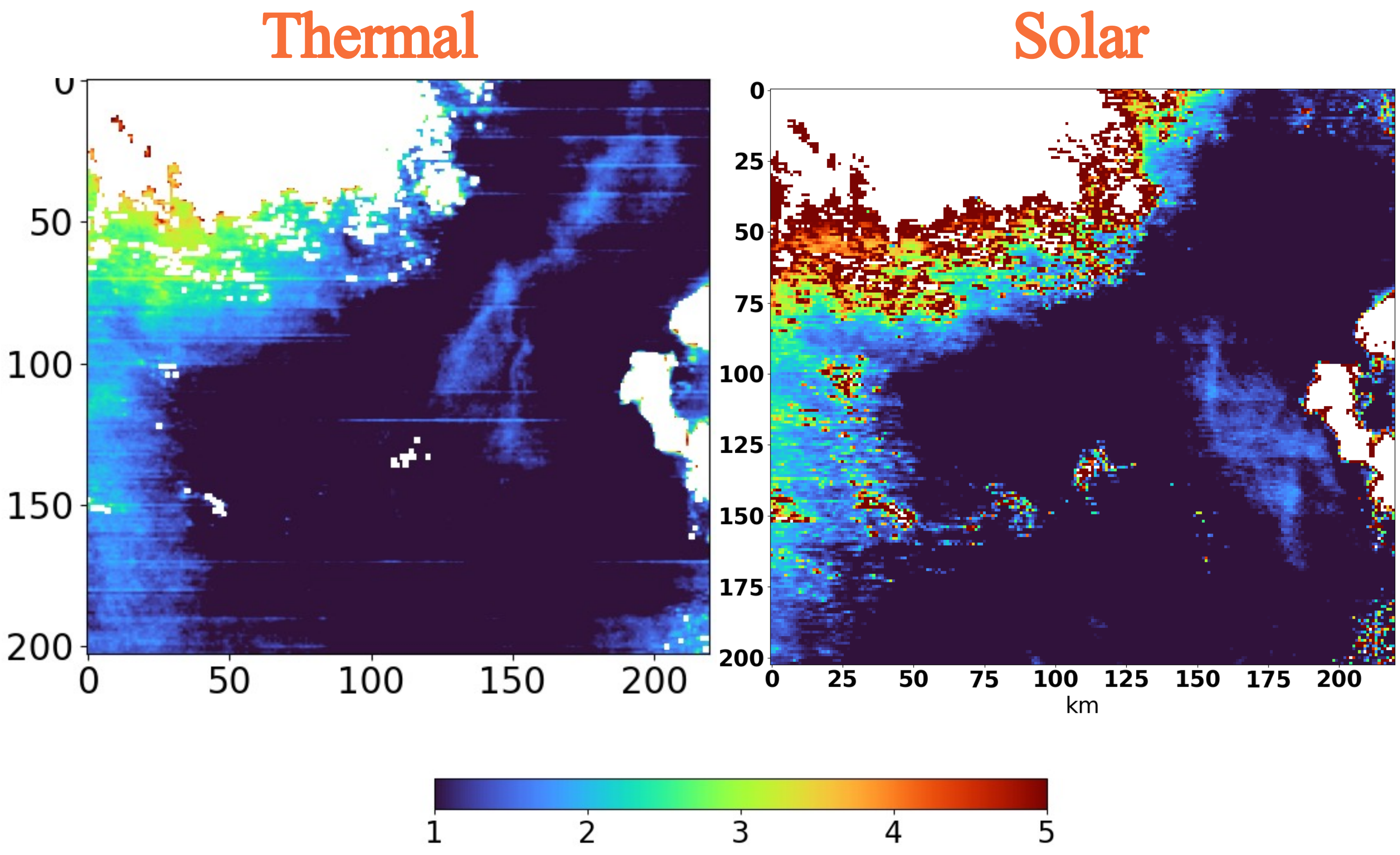




Twilight Spectral Measure (Ψ)

$$\Psi = \frac{1}{N}\sum_{\lambda}\frac{\sqrt{\left(I_{pixel}^{\lambda} - {I_{clr}}^{\lambda}\right)^2}}{{\sigma_{clr}}^{\lambda}}$$

Defining **PURE** clear-sky

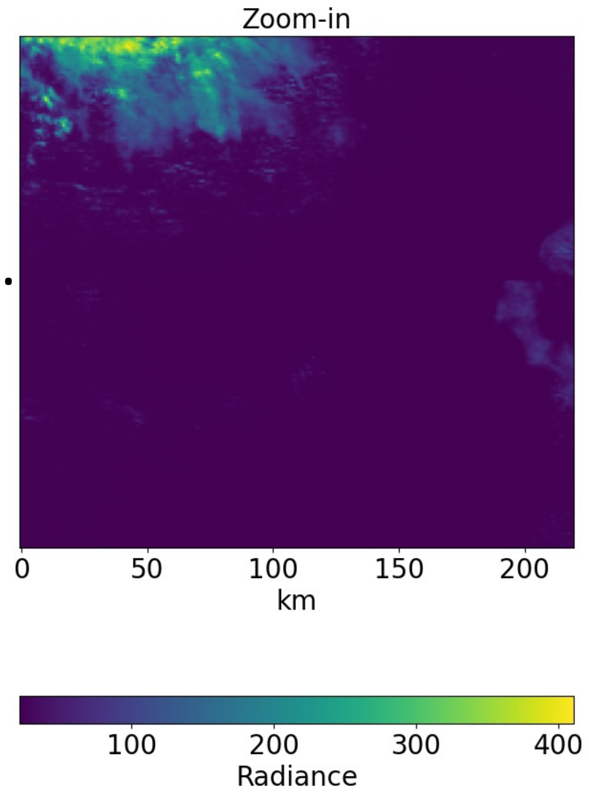


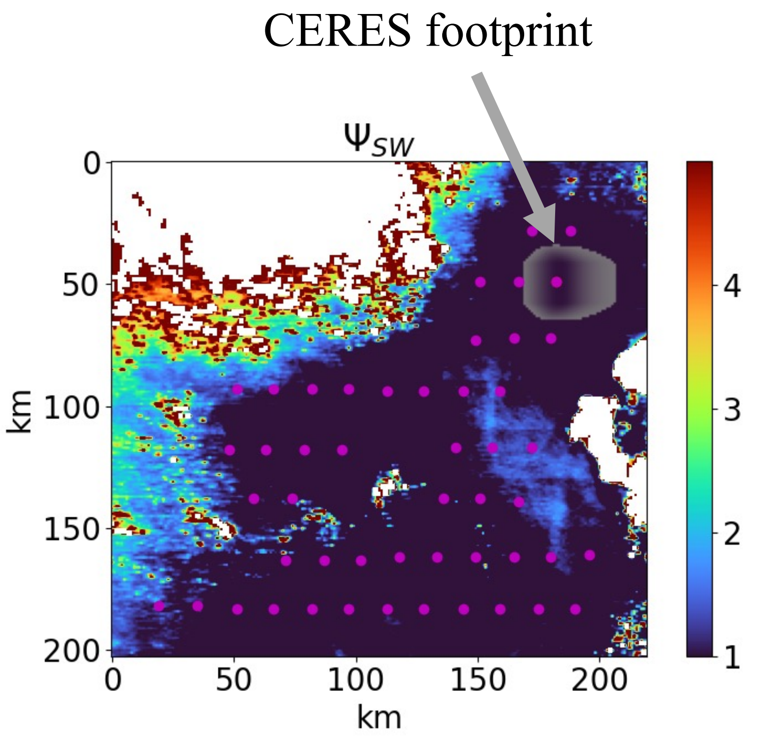
Twilight Spectral Measure (Ψ)

$$\Psi = \frac{1}{N} \sum_{\lambda} \frac{\sqrt{\left(I_{pixel}^{\lambda} - {I_{clr}}^{\lambda}\right)^2}}{{\sigma_{clr}}^{\lambda}}$$

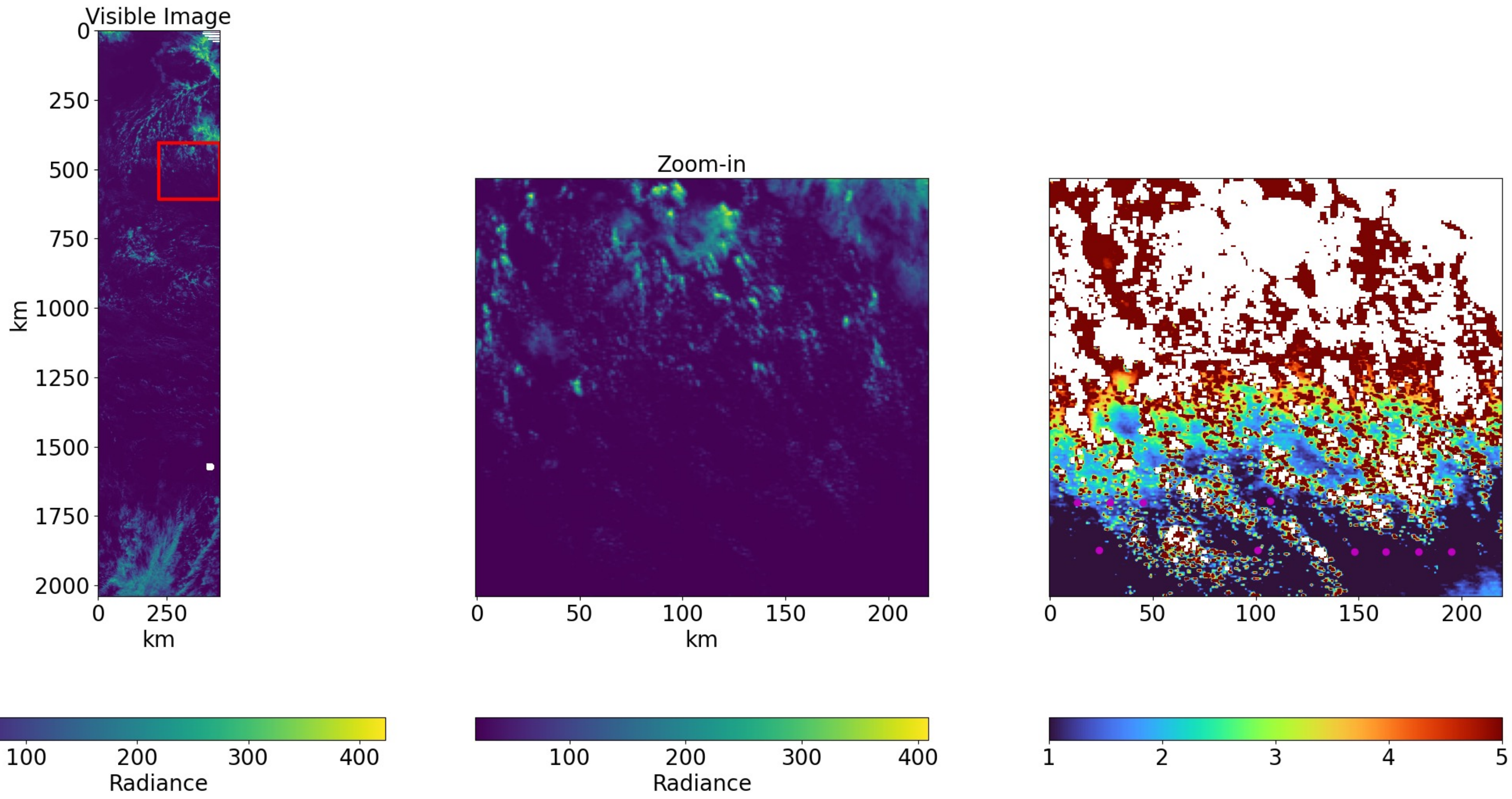
Estimating broadband fluxes from spectral radiance

- Co-locate CERES footprints in the image.
- Average MODIS pixels within the footprint using the Point spread function.
- Take only pure clear sky footprints with all MODIS pixels where Ψ <1, to get pure clear-sky fluxes.

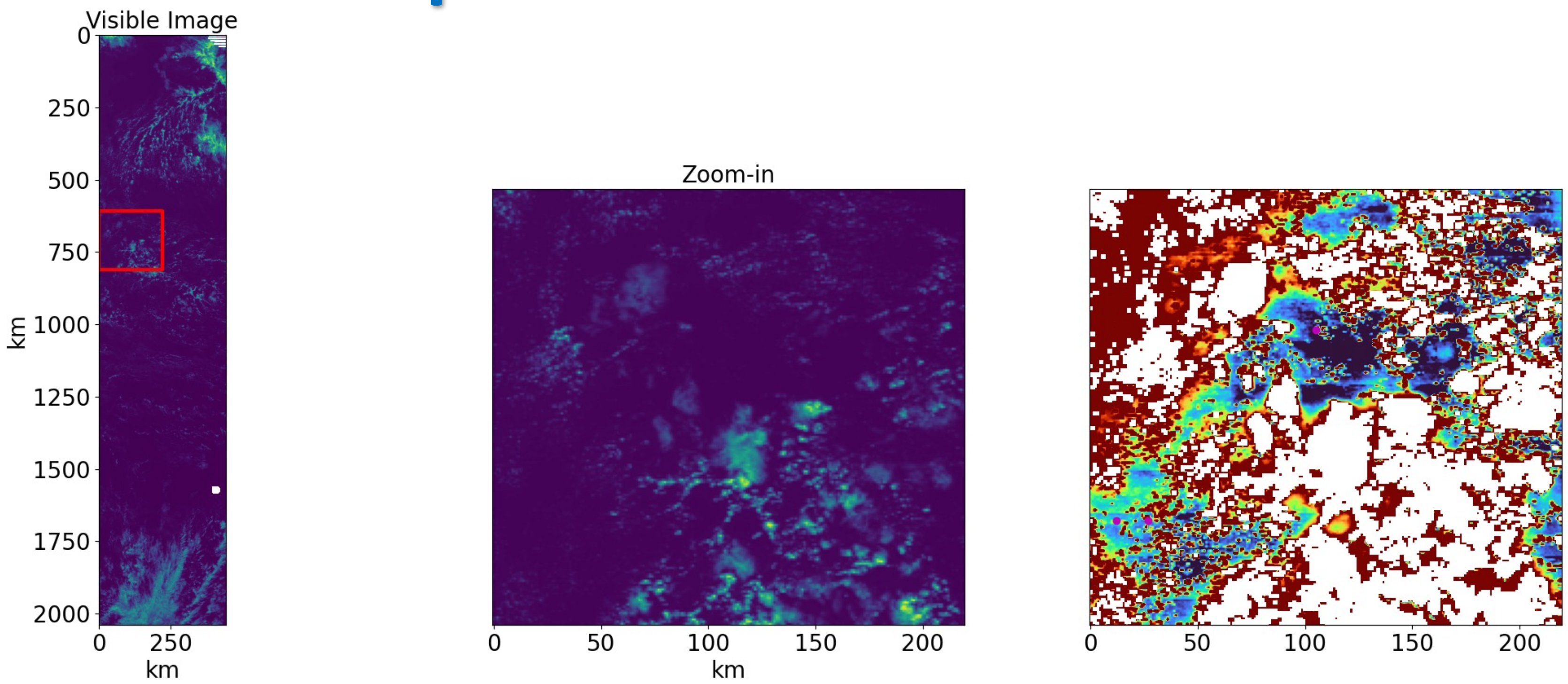




Estimating broadband fluxes from spectral radiance

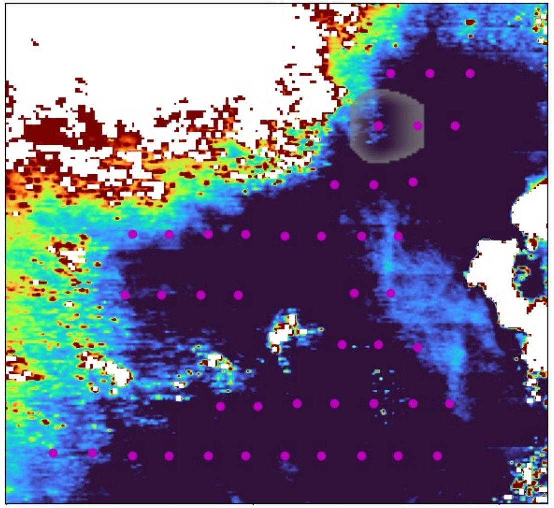


Estimating broadband fluxes from spectral radiance

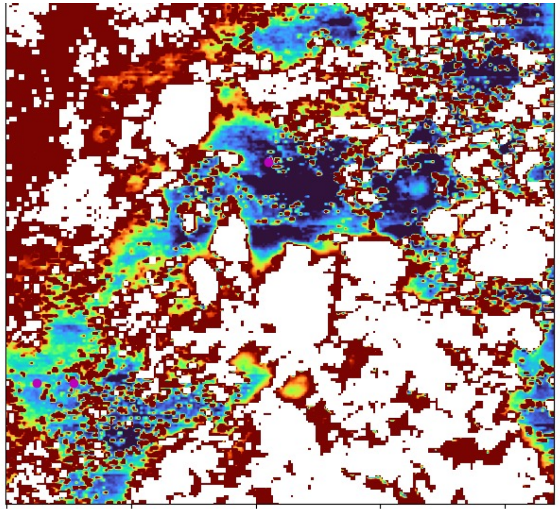


Sometimes CERES just can't get pure clear-sky…

CERES data face two underestimations



1. Demanding that CERES footprints be cloud-free prevents measurements of the most intense regions of the Cloud Twilight Zone



2. Many cloud fields don't have large pure clear-sky voids

Estimating the Cloud Twilight Zone radiative effect

$$CRE = \bar{F}_{all} - \bar{F}_{non-cloudy}$$

$$RE_{tw} = \bar{F}_{non-cloudy} - \bar{F}_{clear}$$

$$RE_{tw} = (\varepsilon - 1)\bar{F}_{clear} = \left(\bar{K}\frac{1}{N_j}\sum_j \frac{\sum_\lambda I_\lambda^j}{\sum_\lambda I_\lambda^{clr}} - 1\right)\bar{F}_{clear}$$

$\bar{F}_{clear}$ - "pure" clear sky flux; $\bar{F}_{non-cloudy}$ - Classical clear sky flux definition; RE_{tw}- "Cloud twilight zone" radiative effect

j- non-cloudy pixel index

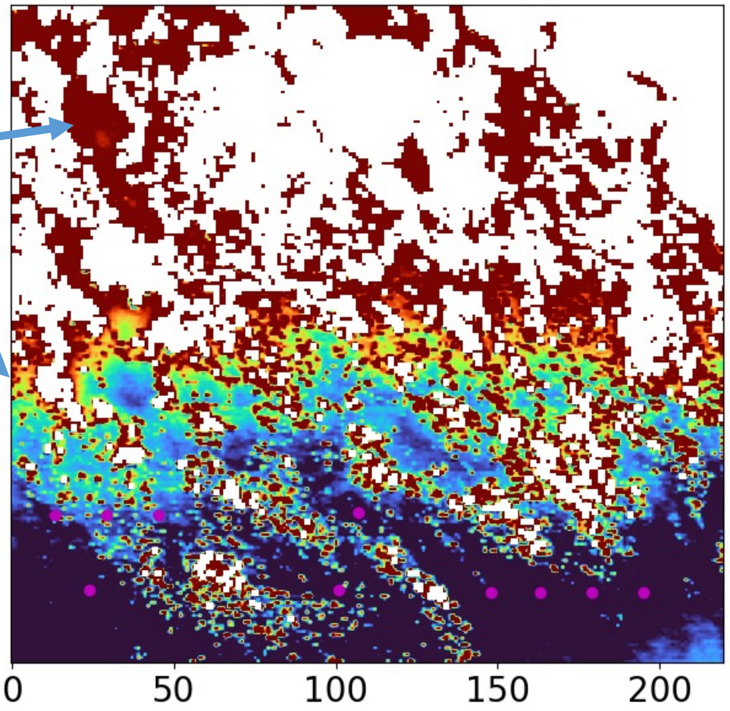
Estimating the Cloud Twilight Zone radiative effect

$$RE_{tw} = (\bar{K}\frac{1}{N_j}\sum_j \frac{\sum_\lambda I_\lambda^{nc}}{\sum_\lambda I_\lambda^{clr}} - 1)F_{clr}$$

MODIS

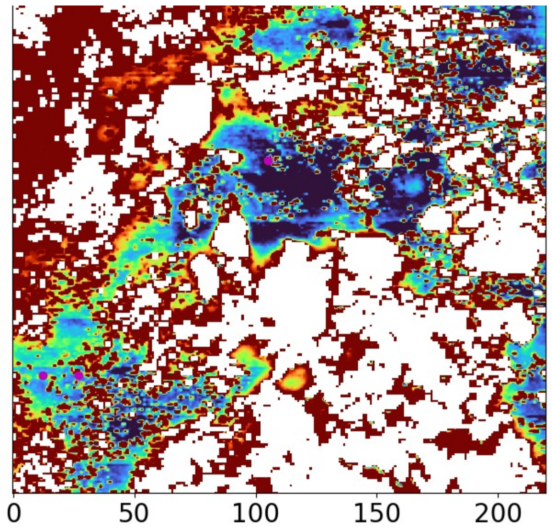
Converts discrete radiance measurements to Broadband irradiance

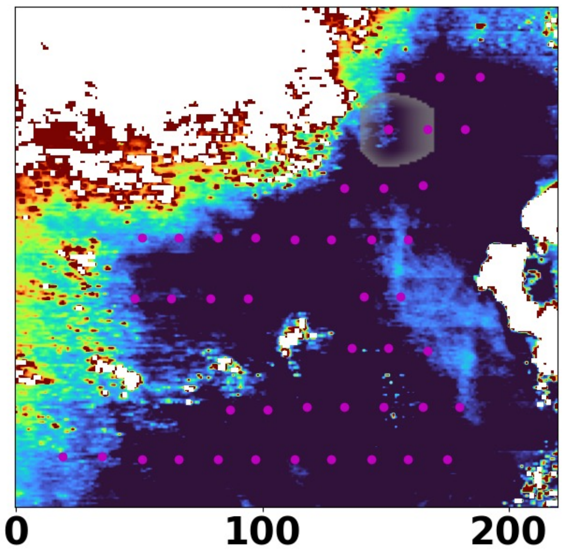
CERES

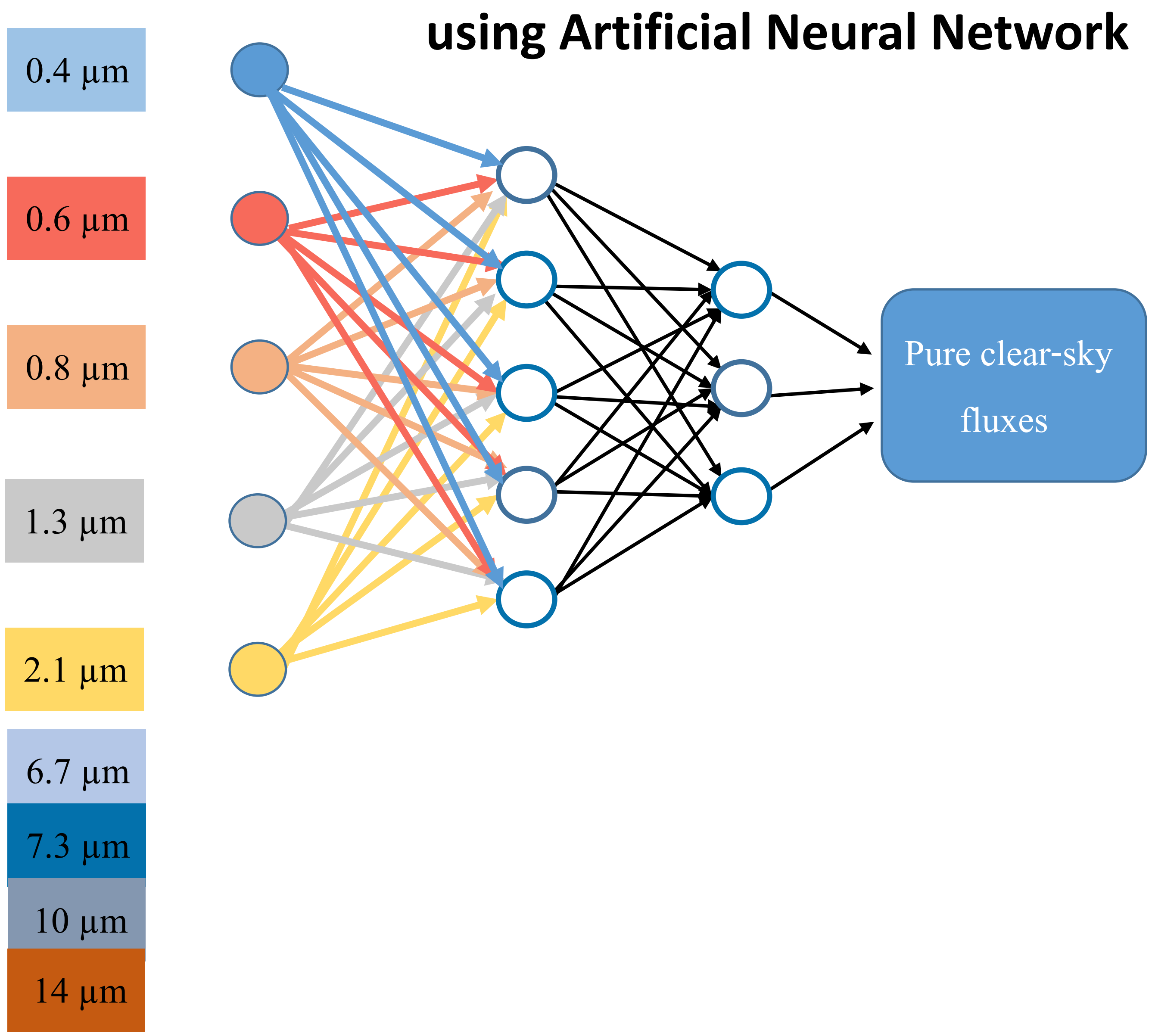


$\bar{F}_{clear}$ - “pure” clear sky flux; $\bar{F}_{non-cloudy}$ - Classical clear sky flux definition; RE_{tw}- “Cloud twilight zone” radiative effect

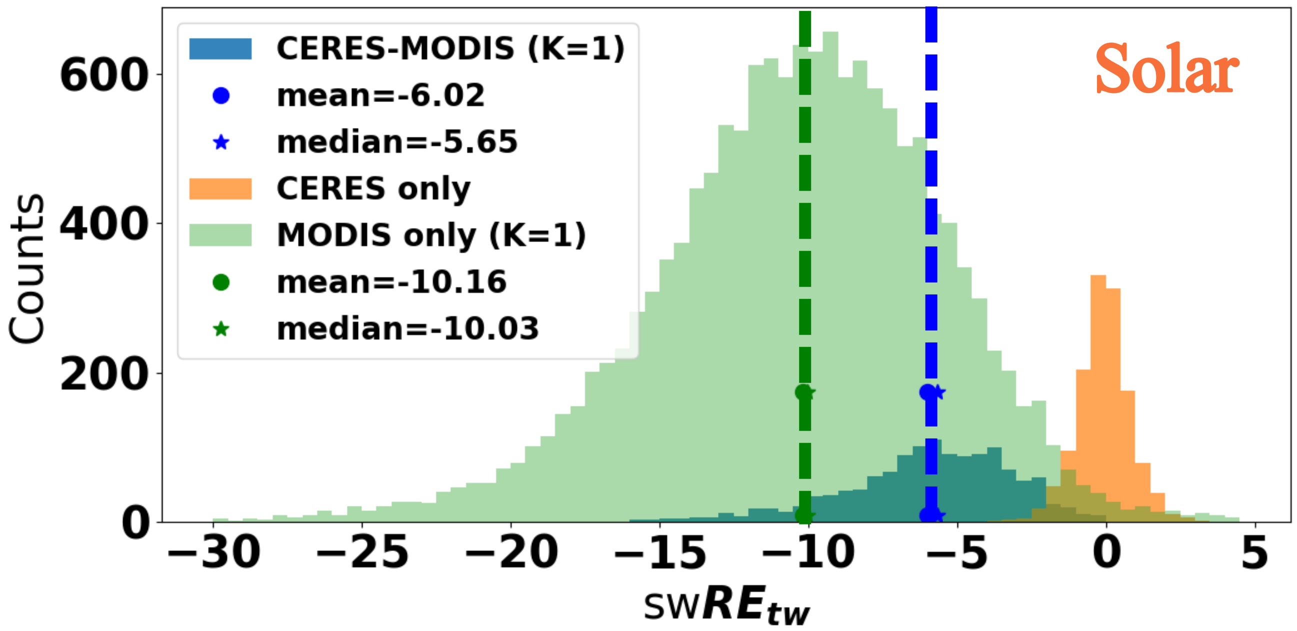
Estimating clear-sky fluxes at a 1 km scale







Estimating cloud twilight zone radiative effect

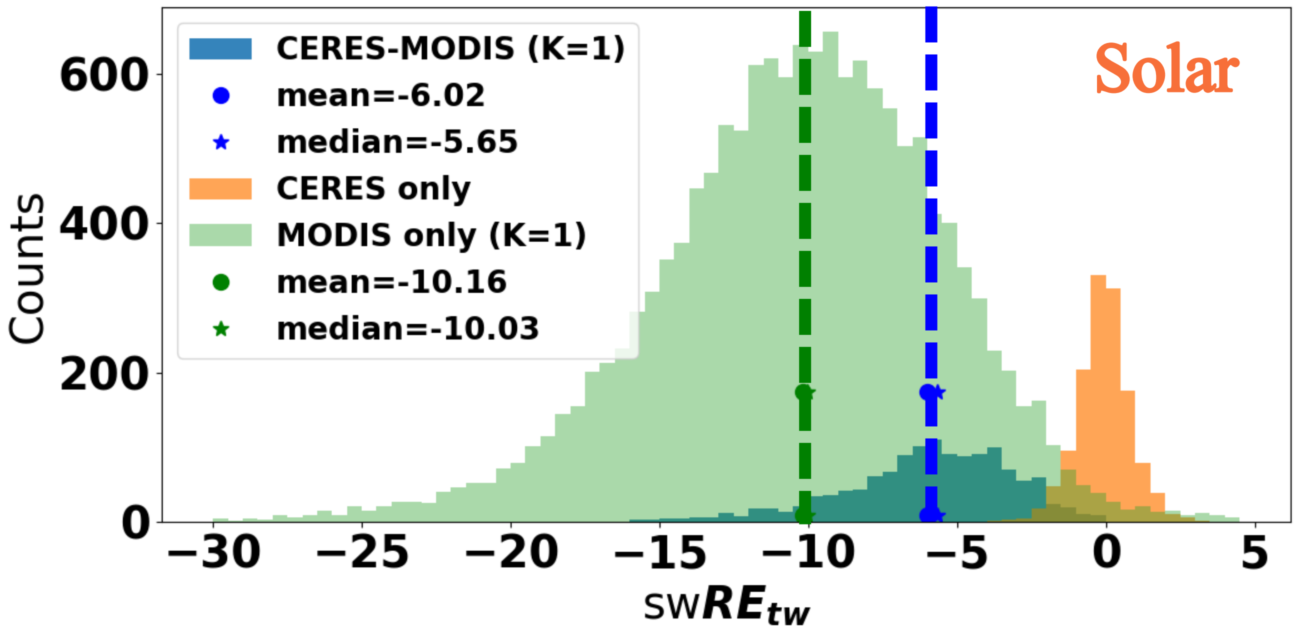


$$RE_{tw} = F_{nc} - F_{clr} = \left(\bar{K}\sum_{j}\frac{\sum_{ch} I_{ch}^{nc}}{\sum_{ch} I_{ch}^{clr}} - 1\right)F_{clr} = \left(\bar{K}\sum_{j}\frac{\sum_{ch} I_{ch}^{nc}}{\sum_{ch} I_{ch}^{clr}} - 1\right)F_{clr}$$

K=1 MODIS CERES

K=1 MODIS

Estimating cloud twilight zone radiative effect

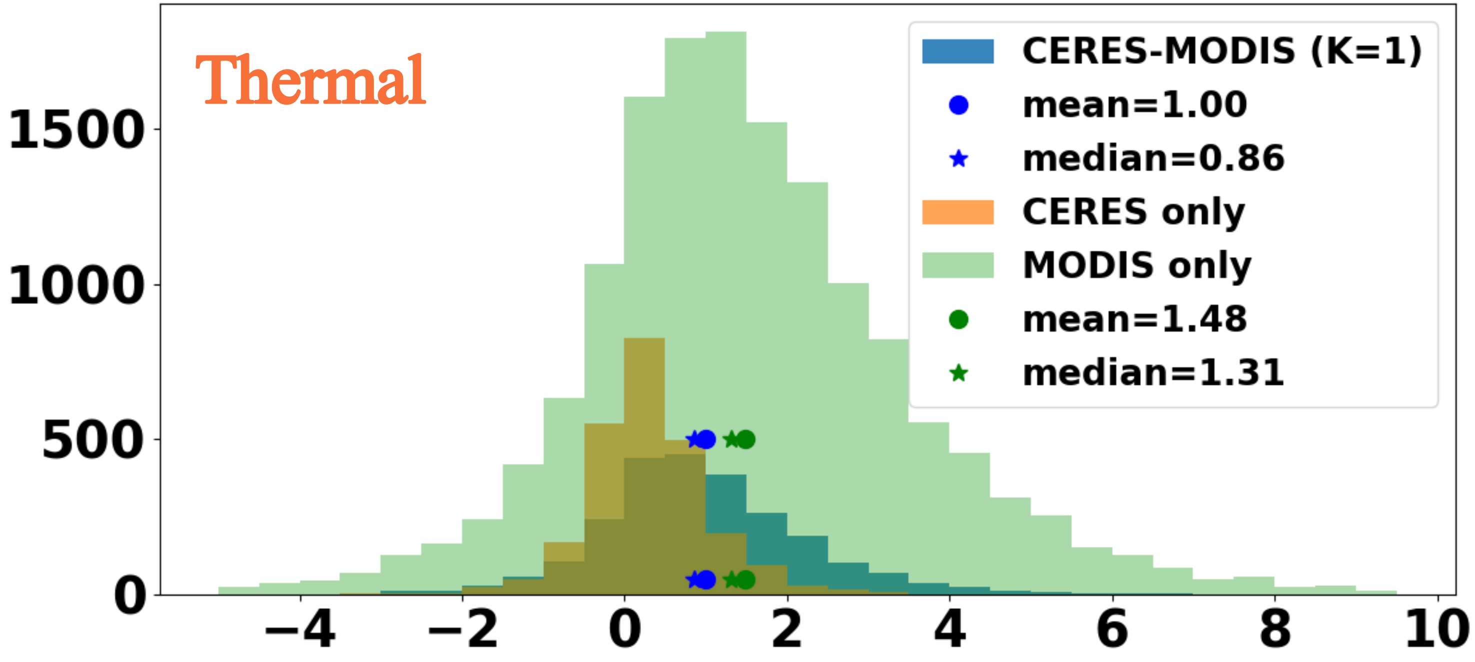


$$RE_{tw} = F_{nc} - F_{clr} = \left(\bar{K}\sum_{j}\frac{\sum_{ch} I_{ch}^{nc}}{\sum_{ch} I_{ch}^{clr}} - 1\right)F_{clr} = \left(\bar{K}\sum_{j}\frac{\sum_{ch} I_{ch}^{nc}}{\sum_{ch} I_{ch}^{clr}} - 1\right)F_{clr}$$

Relaxed cloud mask: $\approx -6\,Wm^{-2}$ $\approx -10\,Wm^{-2}$

Confident cloud mask: $\approx -4.4\,Wm^{-2}$ $\approx -7.4\,Wm^{-2}$

Estimating cloud twilight zone radiative effect



$$RE_{tw} = F_{nc} - F_{clr} = \left(\bar{K}\sum_j \frac{\sum_{ch} I_{ch}^{nc}}{\sum_{ch} I_{ch}^{clr}} - 1\right)F_{clr} = \left(\bar{K}\sum_j \frac{\sum_{ch} I_{ch}^{nc}}{\sum_{ch} I_{ch}^{clr}} - 1\right)F_{clr}$$

$\approx 1\, Wm^{-2}$ $\approx 1.5\, Wm^{-2}$

Summary

- The spectral signature of **pure** clear-sky is obtained from MODIS measurements.

- Co-location of CERES fields of view with MODIS images allows estimation of pure clear-sky radiative fluxes (with regression models) and the Cloud twilight zone radiative effect (RE).

- The cloud twilight zone radiative effect (RE_{tw}) in the *longwave* over the Pacific Ocean was found to be ~1 Wm^{-2} for all clouds and ~0.6 Wm^{-2} for low clouds (close to Eytan et al., 2020 and Jahani et al., 2022)

- In the *shortwave* the cloud twilight radiative effect is ~-10 Wm^{-2}, which is larger than the estimated aerosol direct radiative effect over the Pacific Ocean.

eshkol.eytan@noaa.gov

Conclusions

- Cloud radiative effects are so large that even their weakest effects are equivalent to a very strong clear-sky radiative signature.

- Since it is hard to separate cloud and aerosol direct radiative effects (aerosol affects cloud radiative properties and cloud affects aerosol) it might be better to use the concept of *cloud field radiative effect*.

- What are the controlling factors of RE_{tw}? E.g., aerosol, cloud organization, humidity etc. ?

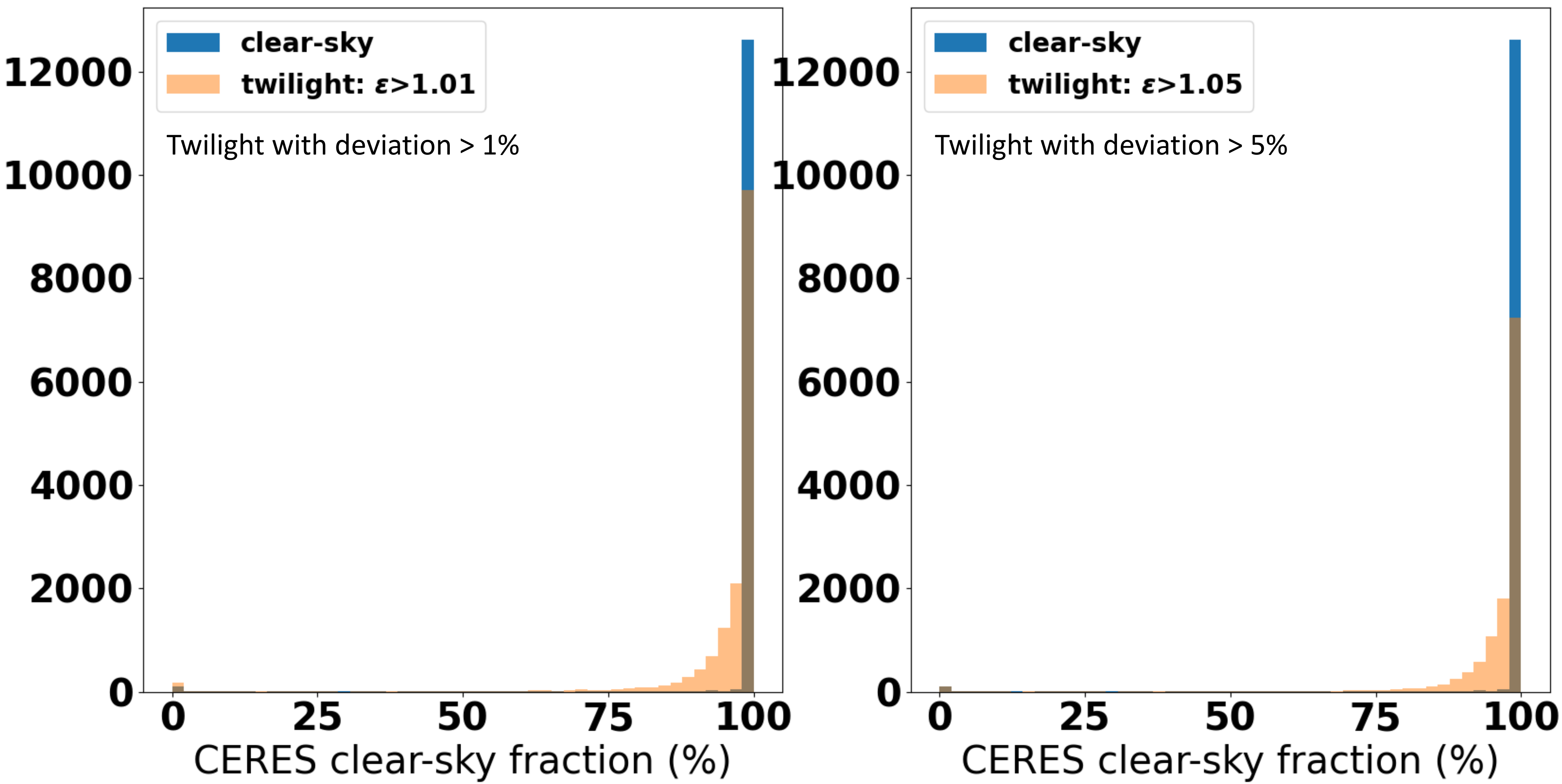
eshkol.eytan@noaa.gov

Thank you for listening

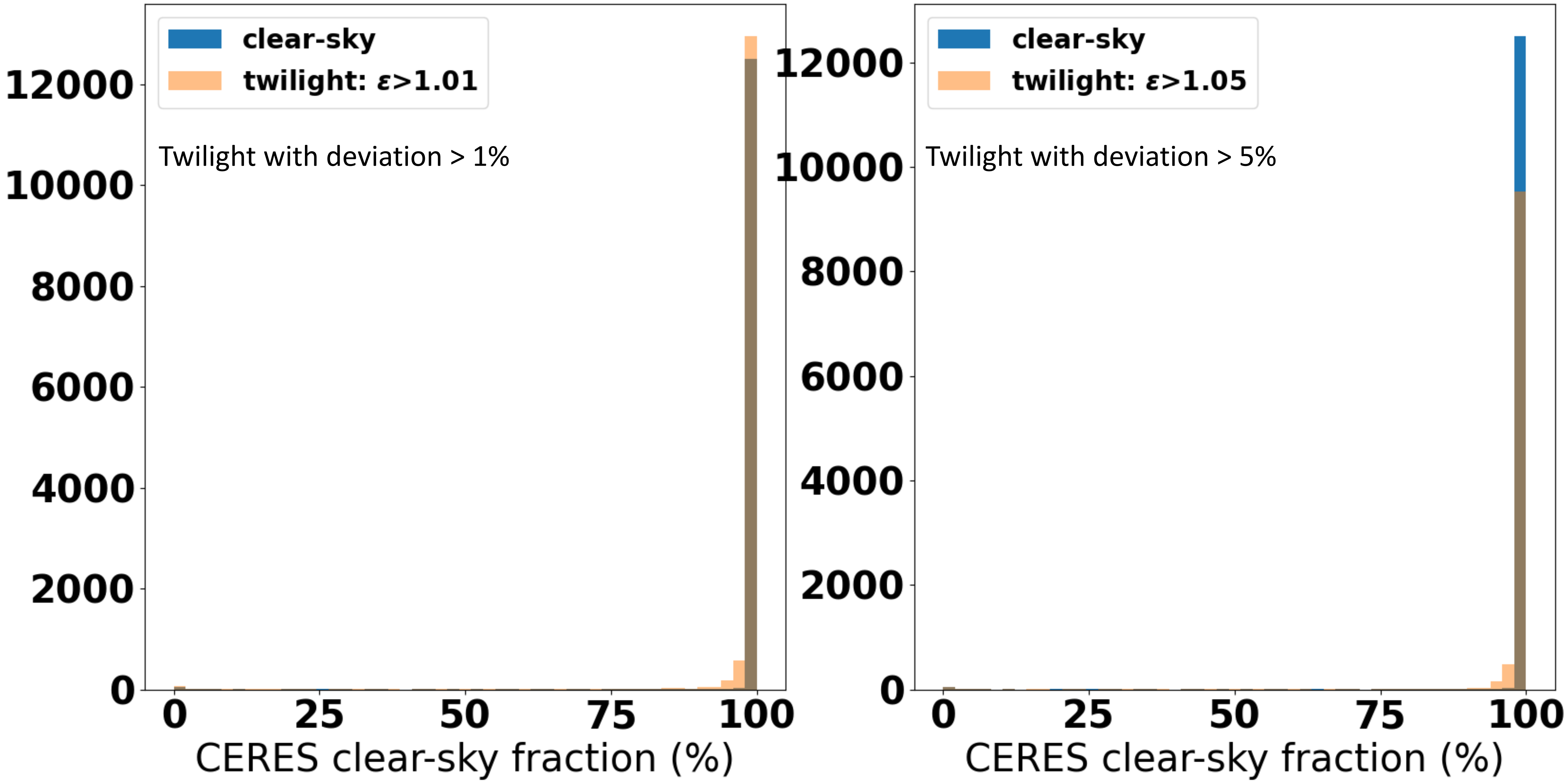
Questions?

eshkol.eytan@noaa.gov

Strict cloud mask



Relaxed cloud mask



For that we adjust the TOA radiation budget equation.

(1) $F_{all} = CF \cdot F_{cld} + (1 - CF)F_{nc}$

(2) $F_{all} = \mathrm{CF} \cdot F_{cld} + (1 - \mathrm{CF})\boldsymbol{F_{clr}} \cdot \varepsilon$

(3) $\varepsilon = \frac{F_{nc}}{F_{clr}} = \bar{K}\frac{1}{N_j}\sum_j \frac{\sum_{ch} I_{ch}^{nc}}{\sum_{ch} I_{ch}^{clr}} = \frac{\boldsymbol{F_{nc} - F_{clr}}}{F_{clr}} + 1$

(4) $\boldsymbol{RE_{tw} = (\bar{K}\frac{1}{N_j}\sum_j \frac{\sum_{ch} I_{ch}^{nc}}{\sum_{ch} I_{ch}^{clr}} - 1)F_{clr}}$

$\boldsymbol{ch}$: *MODIS channel,*
$\boldsymbol{nc}$: *non cloudy,*
$\boldsymbol{j}$: *non cloudy pixels index*

Measured by MODIS

retrieved by CERES or MODIS-CERES regression models

Represents the domain mean non-cloudy optical deviation from the "pure" clear-sky optics (includes the mean linear regression coefficient for spectral interpolation and the Anisotropic factor).

A function of: SZA, optical thickness, viewing angle, particle size distribution (numerate by importance). Data and 1D RT suggests values of 0.96-1.05. Now working on improving its representation

Estimating cloud twilight zone radiative effect

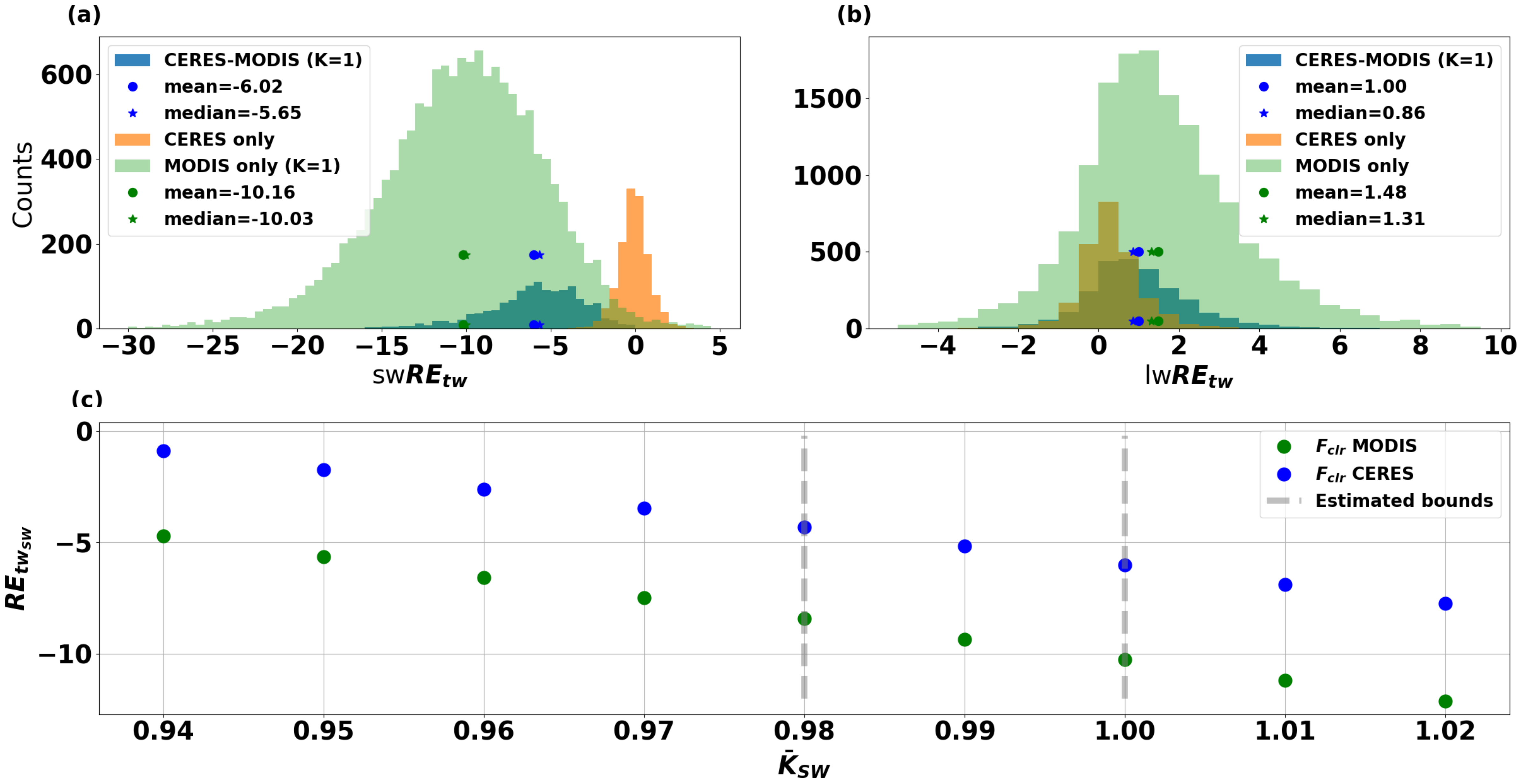


Figure 4: The range of K values from CERES-MODIS dataset

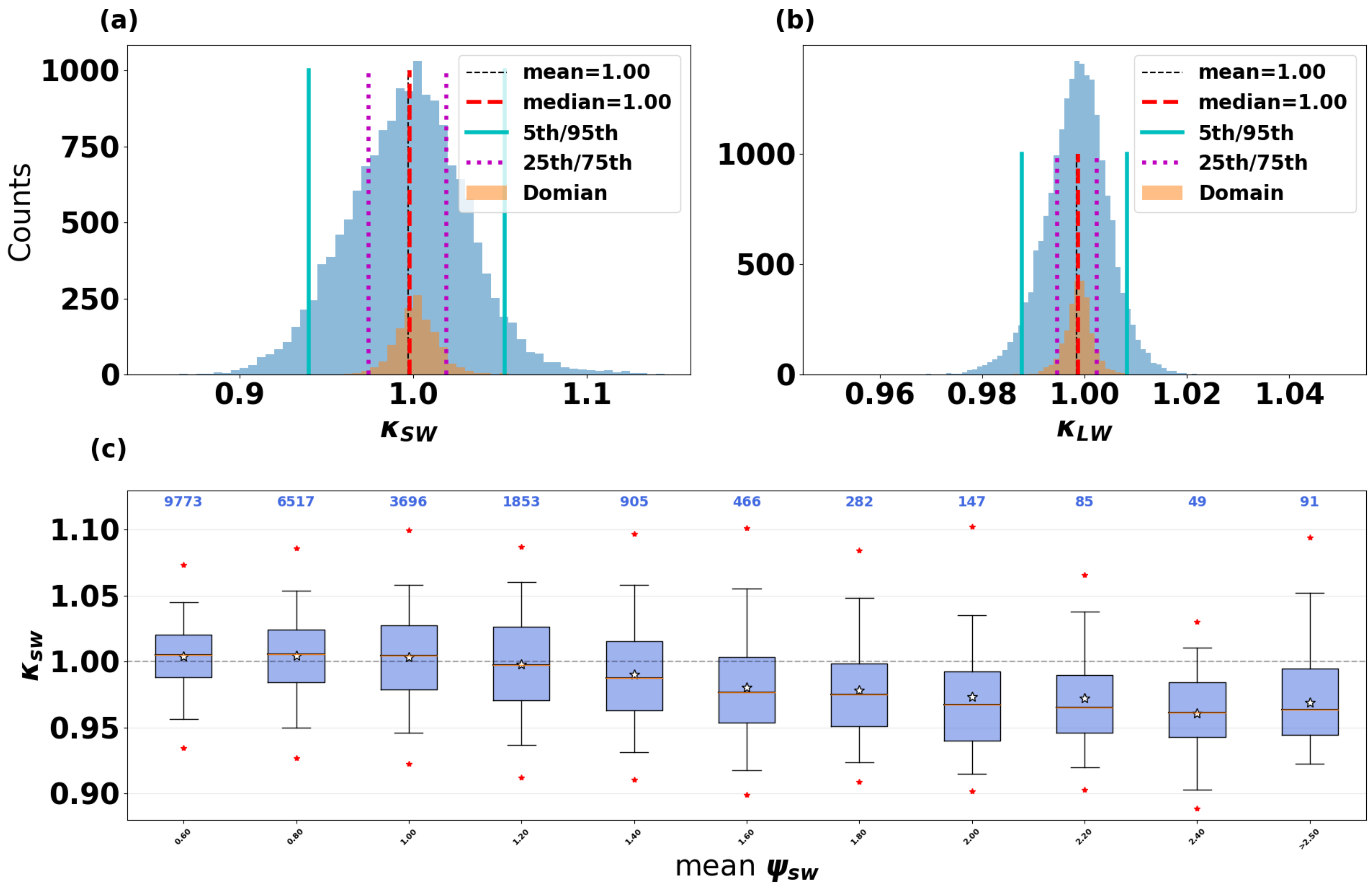
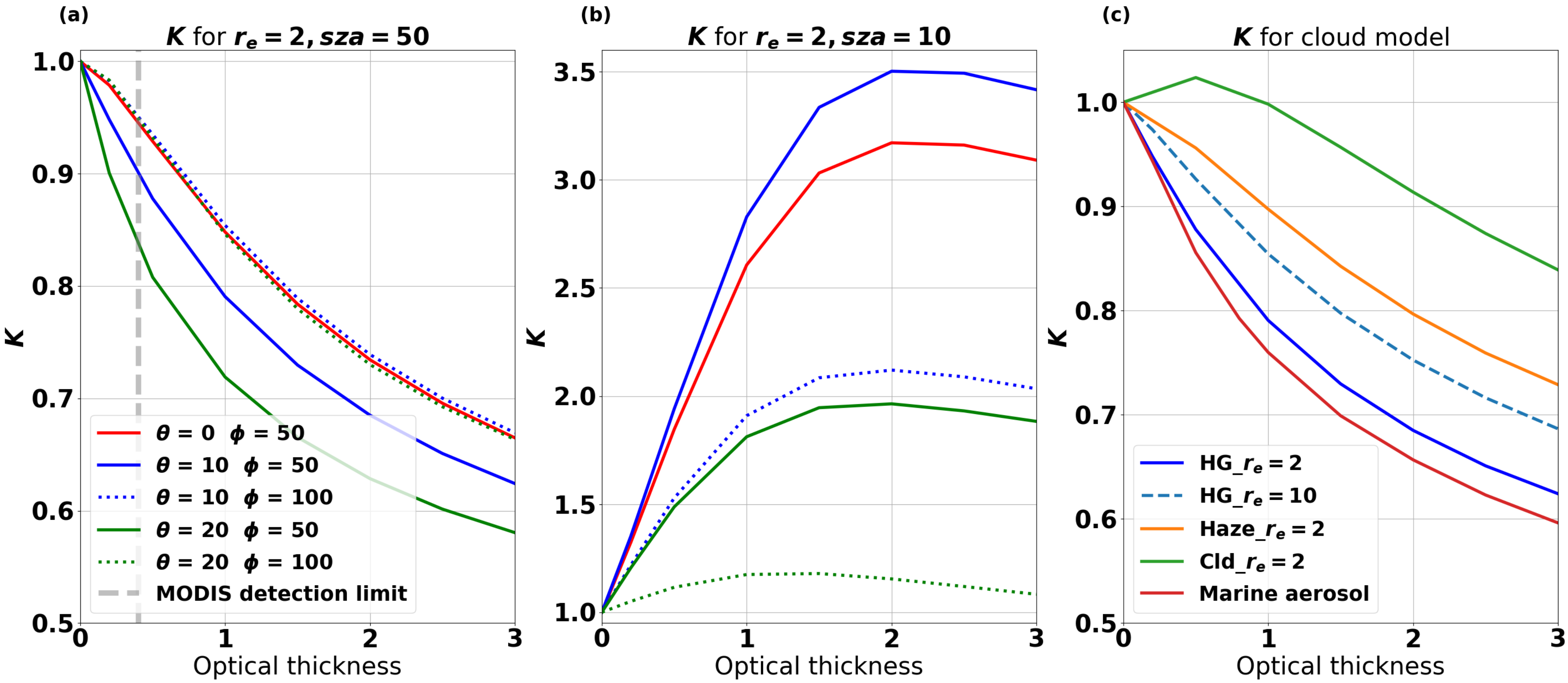
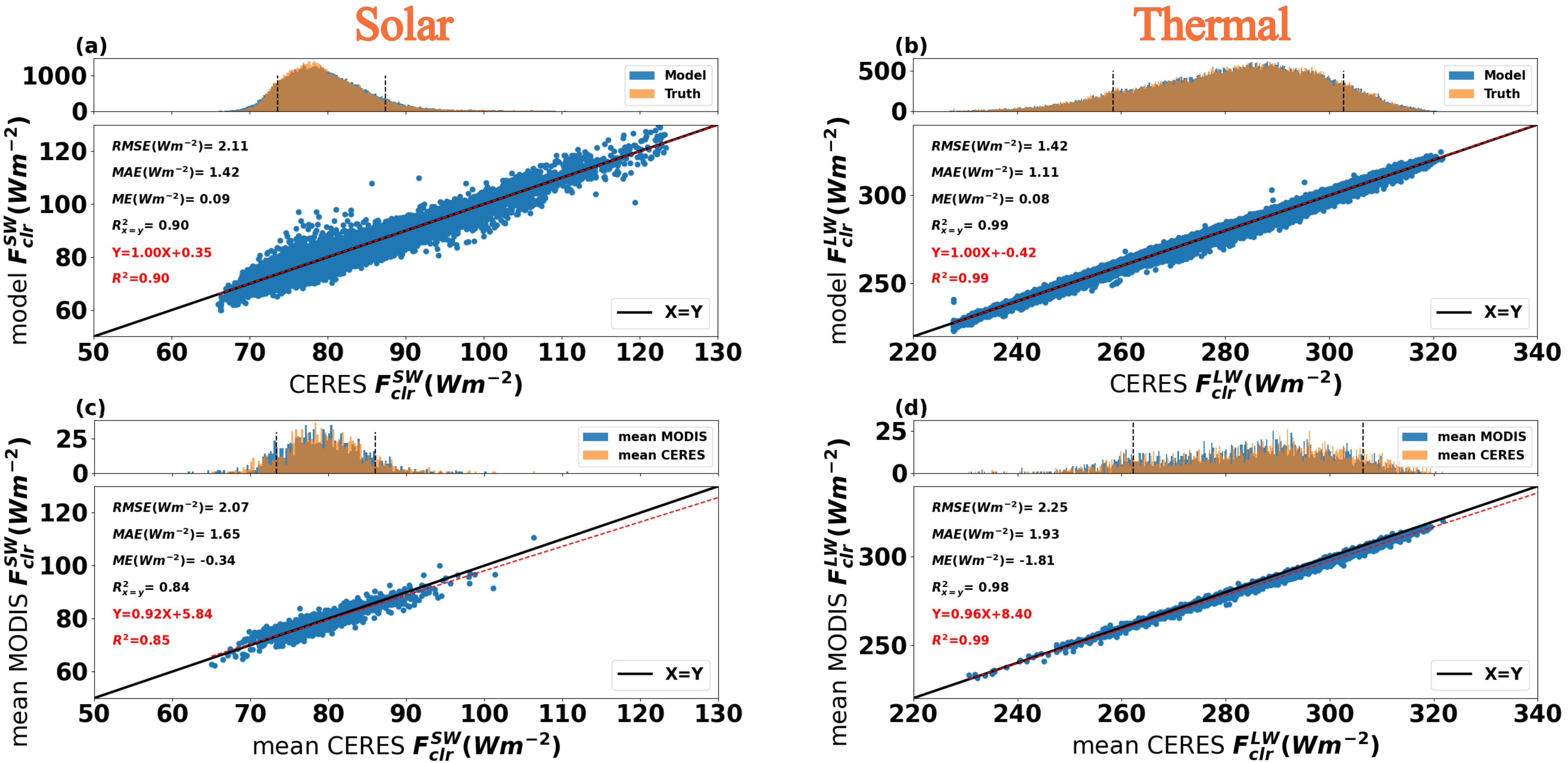


Figure 5: The range of values of K from 1D radiation transfer simulations



1. SZA 2.Optical thickness 3. Viewing angles 4. Cloud model

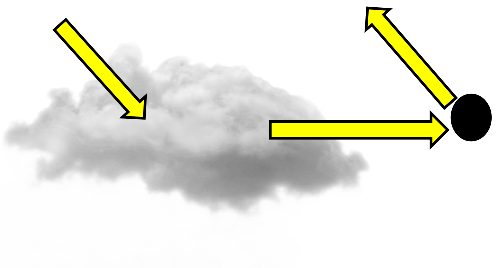
Testing and validating the models



Suggested components in the solar

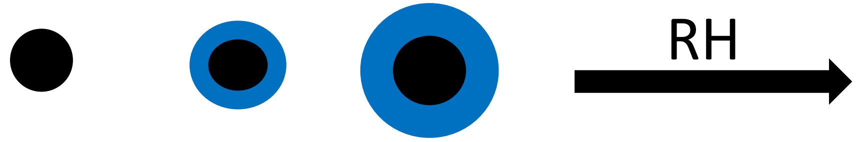
- **3D effect –** Illumination of clear sky by neighboring clouds

  (Wen et al., 2006, Marshak et al., 2008, Varnai et al., 2018).



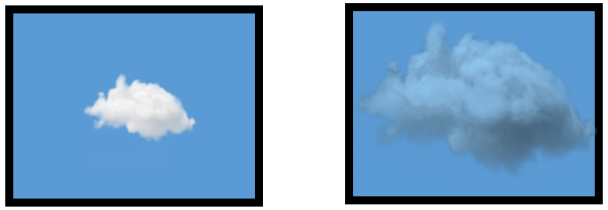
- **Humidified aerosols** – Enlarged cross section of aerosol due to hygroscopic growth near cloud

  (Charlson et al., 2007, Twohy et al., 2009, Bar-Or et al., 2012).

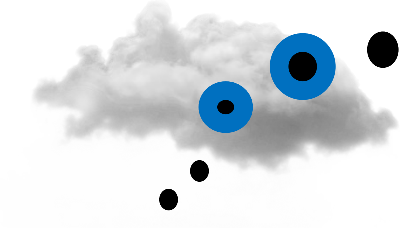


- **Undetected Clouds:**
  - Sub-pixel *(Rodts et al., 2003, Koren et al., 2008).*
  - Optically thin *(Hirsch et al., 2015).*

Sub-pixel Optically thin

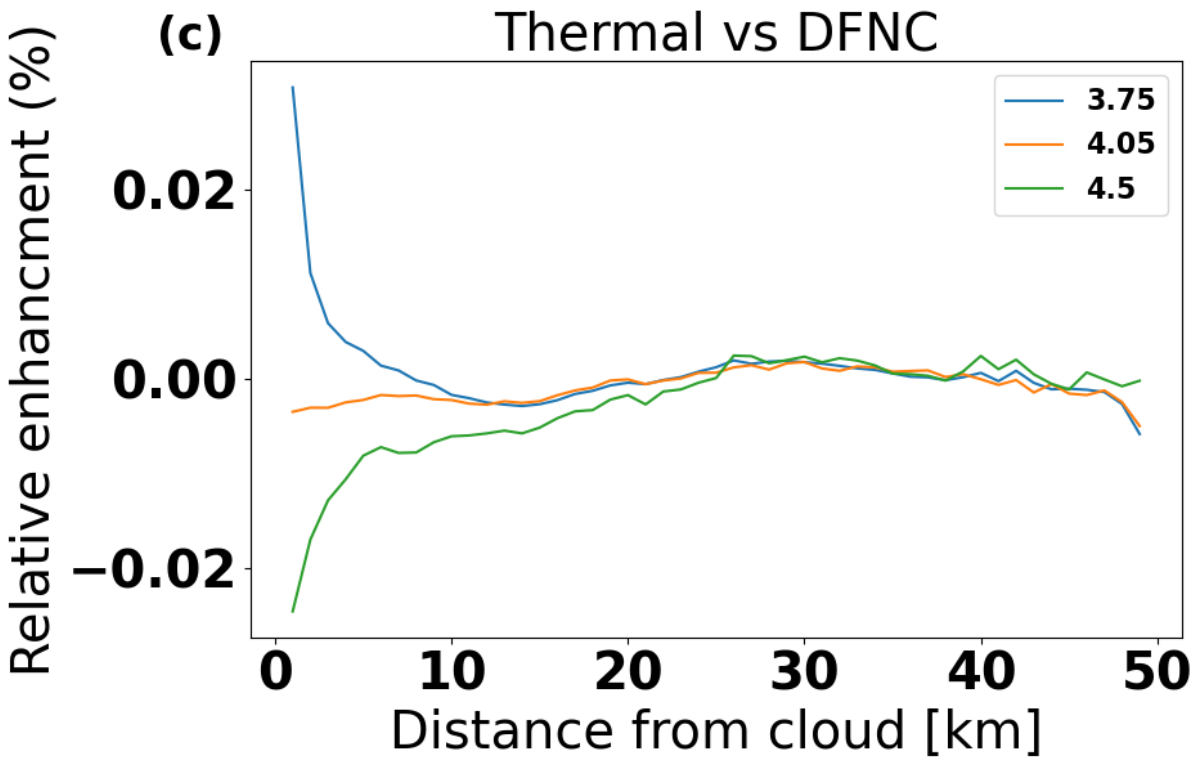


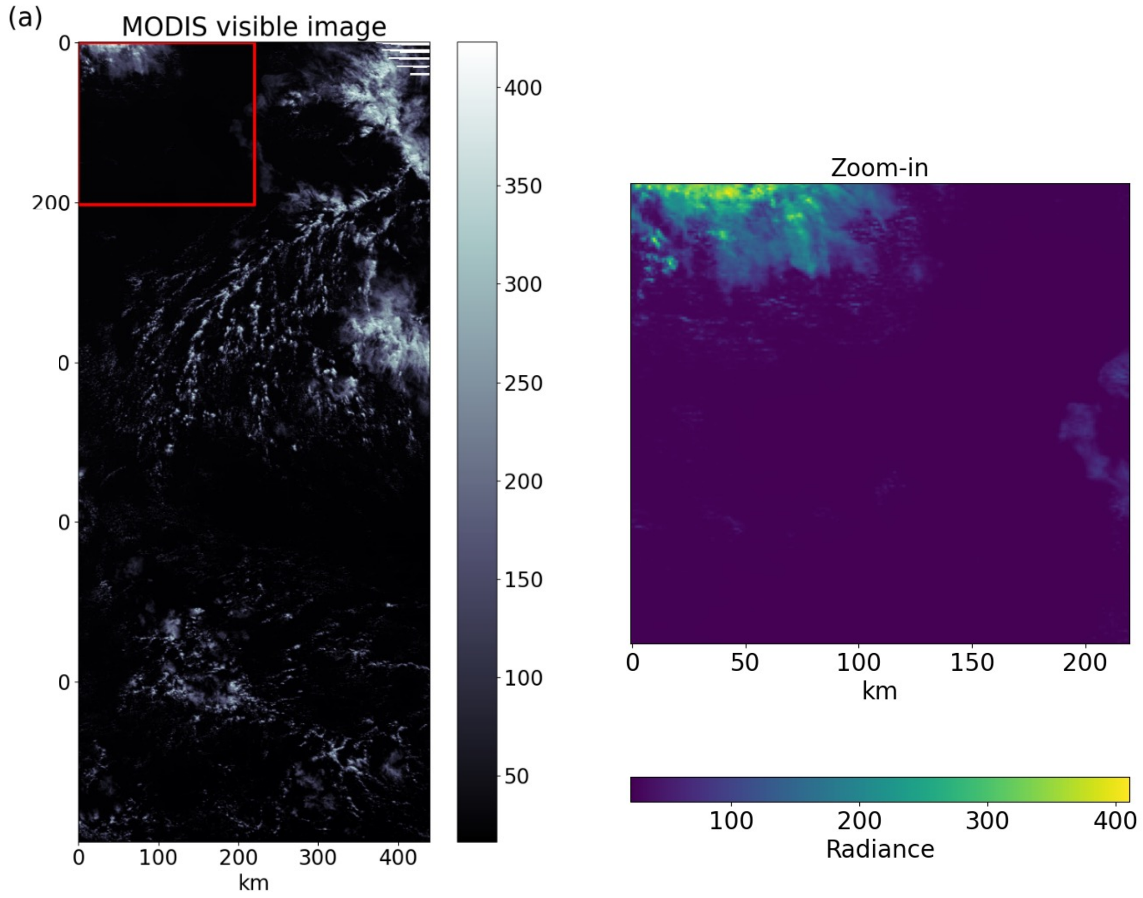
- **Processed aerosols**



Defining **PURE** clear-sky

- Break down MODIS images into small domains of 200x200 km^2.
- Take the distance from cloud profile of each wavelength.
- Construct the **Pure** clear sky spectral distribution ($I_{clr}{}^{\lambda}$).





Adjusting TOA eq. to include cloud effects in clear-sky

(1) $\boldsymbol{F_{all} = CF \cdot F_{cld} + (1 - CF)F_{nc}}$

λ: $MODIS\ channel,$ nc: $non\ cloudy$

Adjusting TOA eq. to include cloud effects in clear-sky

(1) $F_{all} = CF \cdot F_{cld} + (1 - CF)F_{nc}$

(2) $\boldsymbol{F_{all} = \mathrm{CF} \cdot F_{cld} + (1 - \mathrm{CF})F_{clr}\varepsilon}$

λ: $MODIS\ channel,$ nc: $non\ cloudy$

Adjusting TOA eq. to include cloud effects in clear-sky

(1) $F_{all} = CF \cdot F_{cld} + (1 - CF)F_{nc}$

(2) $F_{all} = \mathrm{CF} \cdot F_{cld} + (1 - \mathrm{CF})F_{clr} \cdot \varepsilon$

MODIS

(3) $\boldsymbol{\varepsilon = \frac{F_{nc}}{F_{clr}} = \bar{K} \frac{1}{N_{nc}} \sum_j \frac{\sum_\lambda I_\lambda^{nc}}{\sum_\lambda I_\lambda^{clr}} = \frac{F_{nc} - F_{clr}}{F_{clr}} + 1}$

$$\frac{F_{nc}}{F_{clr}} \equiv K \frac{\sum_\lambda I_\lambda^{nc}}{\sum_\lambda I_\lambda^{clr}}$$

λ: $MODIS\ channel,$ nc: $non\ cloudy$

Adjusting TOA eq. to include cloud effects in clear-sky

(1) $F_{all} = CF \cdot F_{cld} + (1 - CF)F_{nc}$

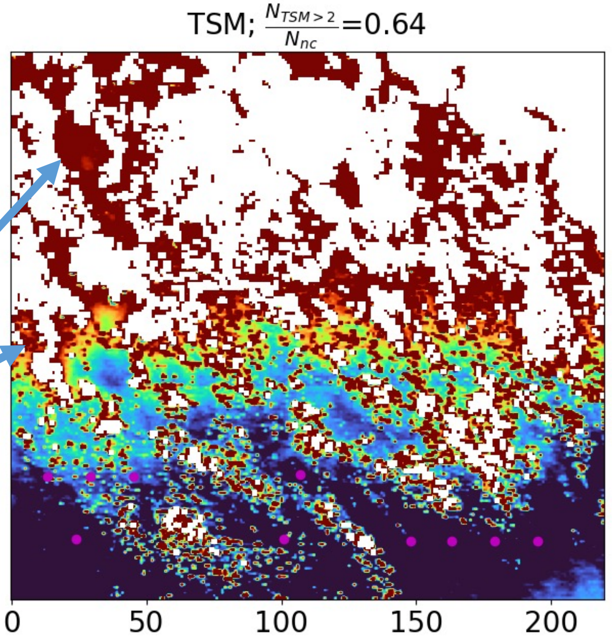
(2) $F_{all} = \mathrm{CF} \cdot F_{cld} + (1 - \mathrm{CF})F_{clr} \cdot \varepsilon$

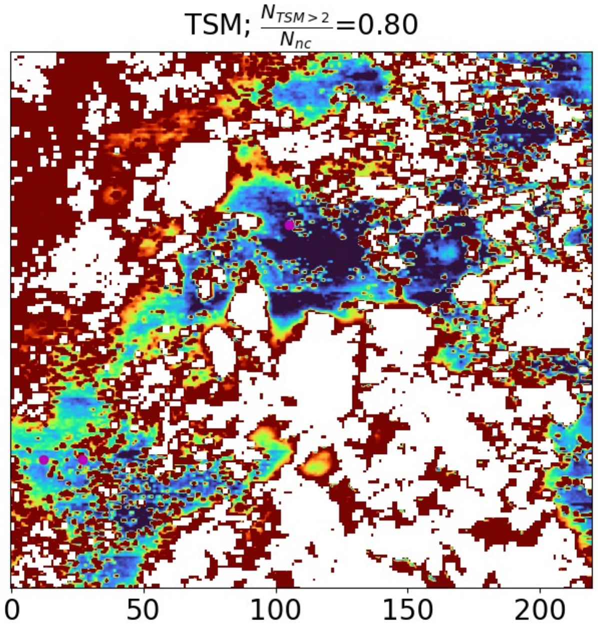
(3) $\varepsilon = \frac{F_{nc}}{F_{clr}} = \bar{K}\sum_j \frac{\sum_\lambda I_\lambda^{nc}}{\sum_\lambda I_\lambda^{clr}} = \frac{F_{nc} - F_{clr}}{F_{clr}} + 1$

(4) $\boldsymbol{RE_{tw} = (\bar{K}\sum_j \frac{\sum_\lambda I_\lambda^{nc}}{\sum_\lambda I_\lambda^{clr}} - 1)F_{clr}}$

MODIS

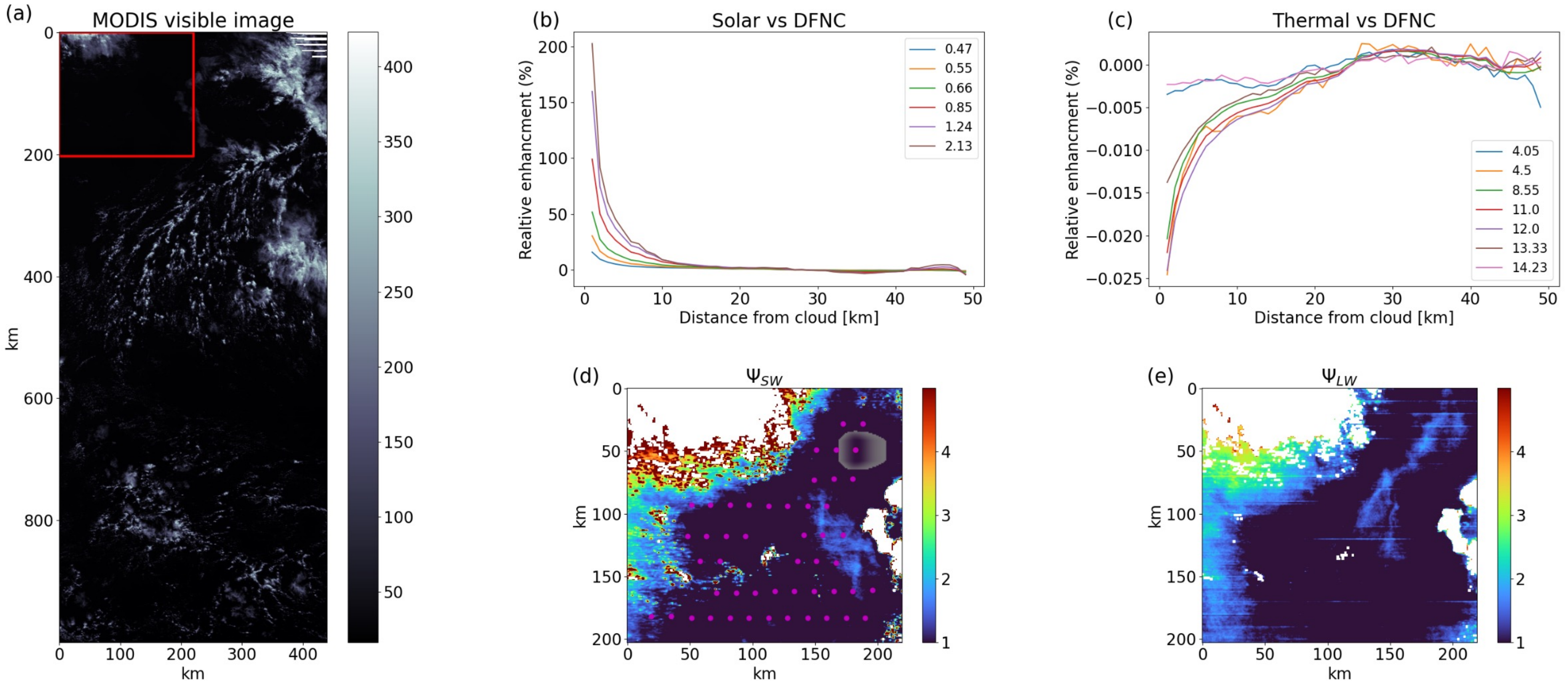
CERES





λ: $MODIS\ channel,$ nc: $non\ cloudy$

Defining



$$\Psi = \sum_{\lambda} \frac{\sqrt{\left(I^{\lambda}_{pixel} - {I_{clr}}^{\lambda}\right)^2}}{{\sigma_{clr}}^{\lambda}} \frac{{I_{clr}}^{\lambda}}{\sum_{\lambda} {I_{clr}}^{\lambda}}$$