ARM shortwave spectrometers to study the clear-cloud transition zone and mixing processes

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Thanks to Connor Flynn

Background (Transition Zone, TZ)

- The TZ between cloudy and clear air is a region of **strong aerosol-cloud interactions** where aerosol CCN **humidify** and **swell** when approaching the cloud, while cloud drops **evaporate** and **shrink** when moving away from the cloud.

- There is a dynamic dance between CCN and cloud drops in this region, but this dance is extremely difficult to study with current aircraft, satellite and with most surface remote sensors because they just **don't have the time and/or spatial resolution** to do so.

- The TZ is also not amenable to textbook microphysics and thermodynamics; it is contaminated by '**weak cloud elements**', such as cloud fragments sheared off from adjacent clouds.

Background (Mixing Processes)

- The Inhomogeneous Mixing Hypothesis. This is a 40-years-old problem that refuses to die. The difference between homogeneous and inhomogeneous mixing is attributed to the **different timescales of mixing and evaporation.**

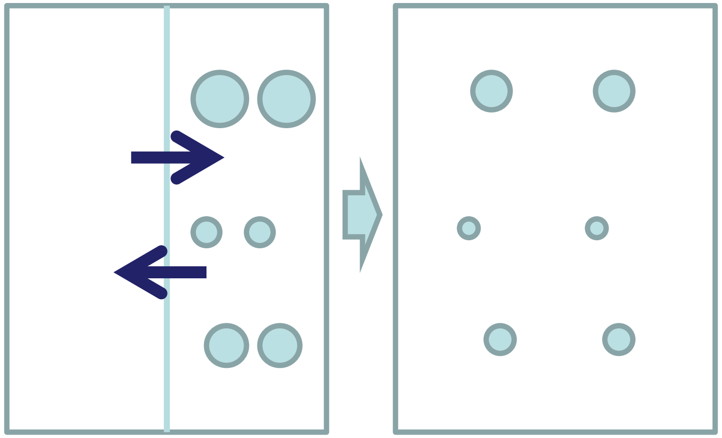
- We use **ground-based spectral observations** to test the inhomogeneous mixing hypothesis in **low clouds**. The information on the mixing processes in cloud-to-clear TZ has been never deduced from ground-based radiation observations.

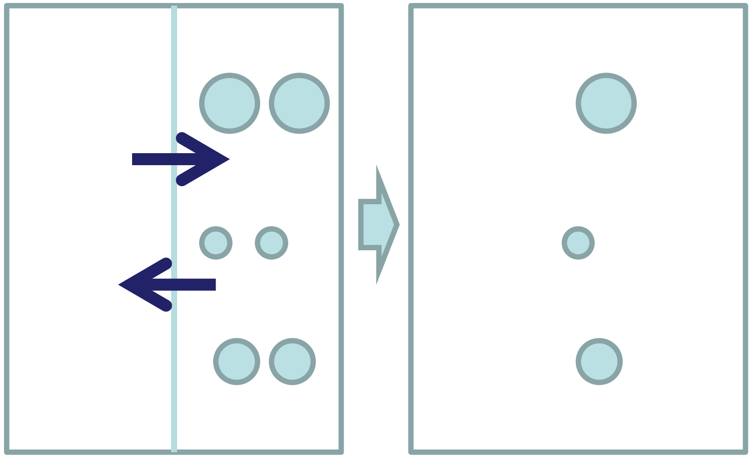
- Data from shortwave spectrometers provide a **unique opportunity** to study the cloud mixing processes.

Two limiting scenarios in mixing clouds and dry air

Homogeneous Mixing
Drier air penetrates the cloud before cloud drop evaporates.

Reduction in size of *all* droplets but no substantial change in the number of cloud droplets.





Inhomogeneous Mixing
Cloud drop evaporates before dry air penetrates the entirety of the cloud.

Reduction in the droplet number concentration for droplets of *all* sizes but no change in the cloud drop spectrum.

e.g. Baker et al. (1980); Baker and Latham (1982); Lehmann et al., (2009); Lu et al., (2013); Korolev et al., 2016; Pinsky et al., 2016a,b, 2018; Lu et al., 2018; Gao et al., 2018.

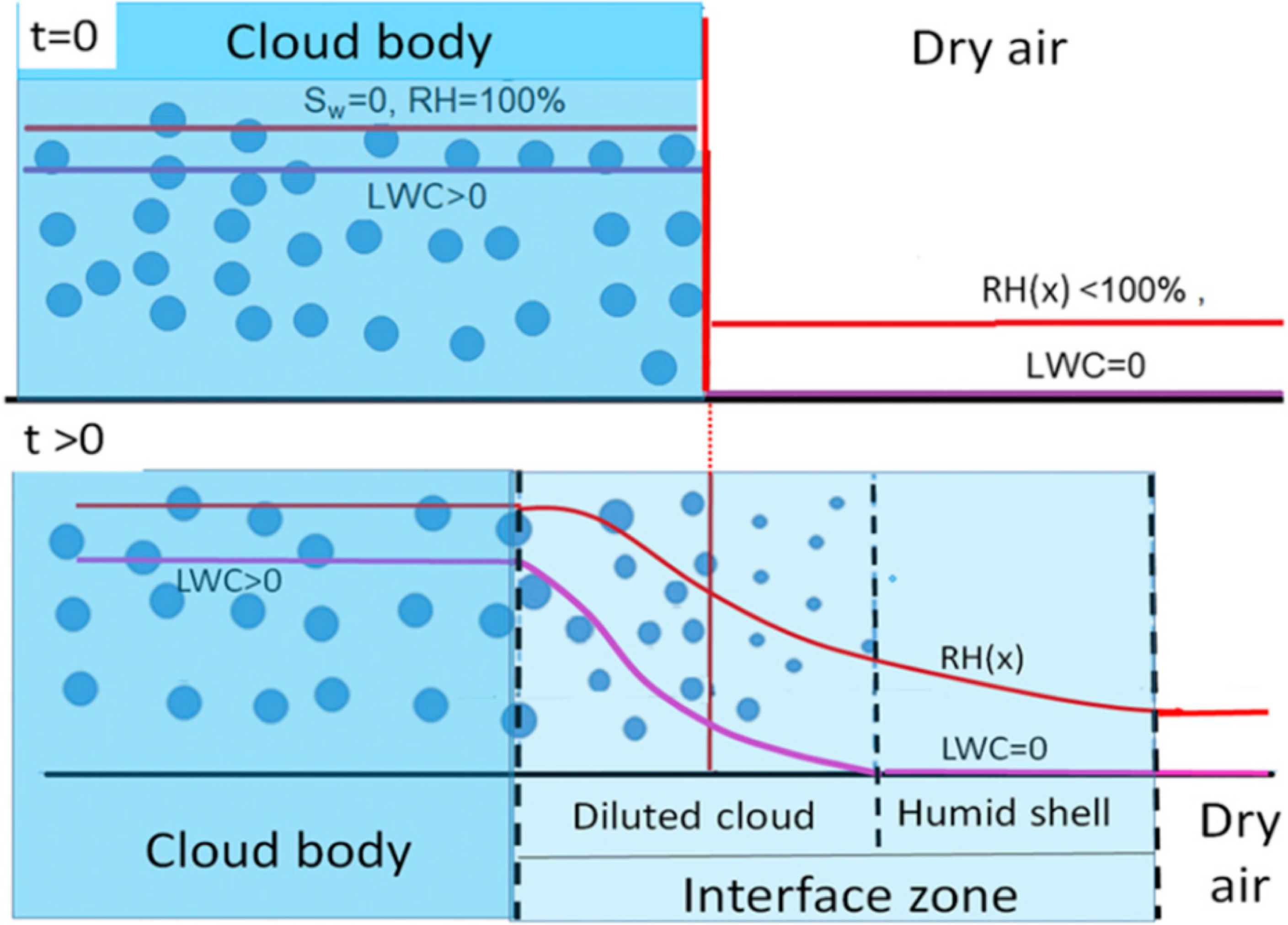
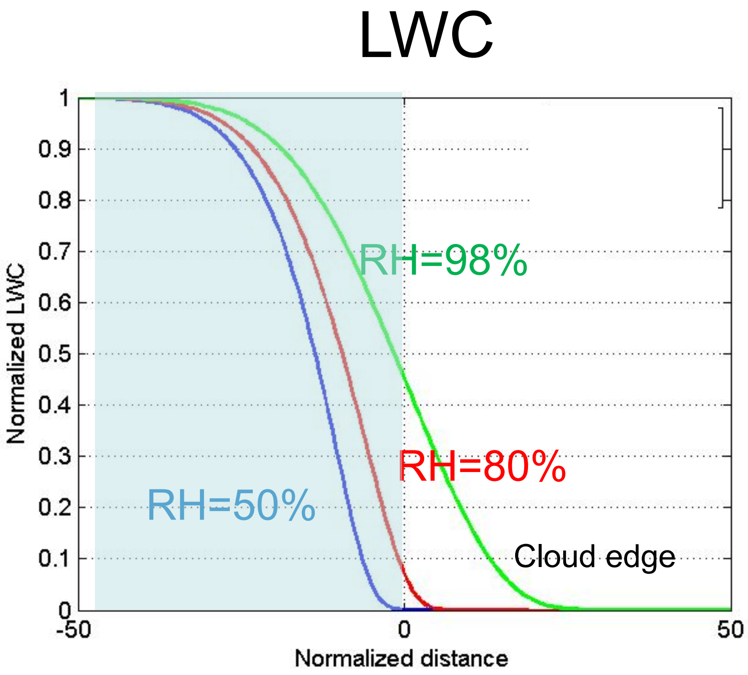
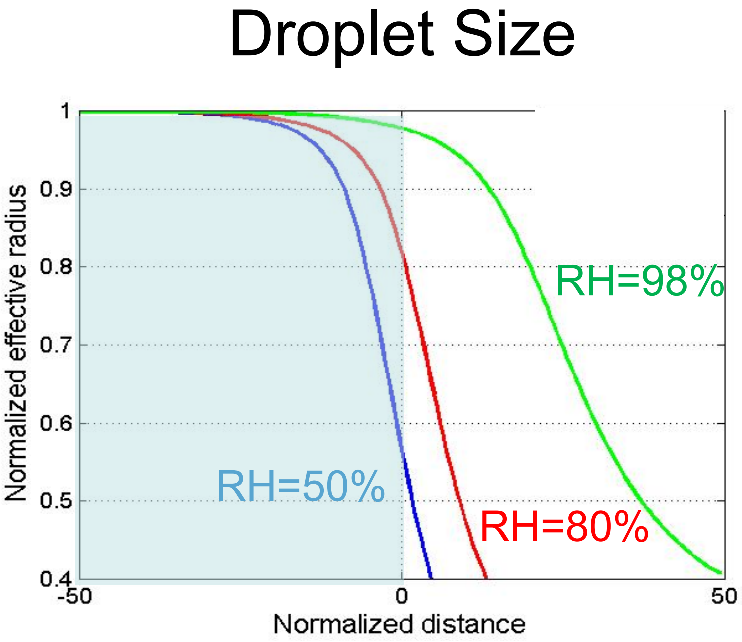


FIG. 1. Conceptual scheme of zones in the vicinity of the cloud–air interface. Upper panel corresponds to $t = 0$. Lower panel shows the developed interface zone.

From Pinsky and Khain, JAS 2018

Radial profiles of LWC and effective radius





Effective radius remains unchanged within a significant fraction of dilution zone, despite decrease in LWC at cloud edge

Dealing with ARM spectral data

To analyze ground-based spectral observations in the TZ we developed a new “**spectral invariant**“ approach

Spectral-invariant hypothesis

Zenith radiance spectrum in the TZ is a linear combination of cloudy and clear sky spectra with a wavelength-independent weighting functions

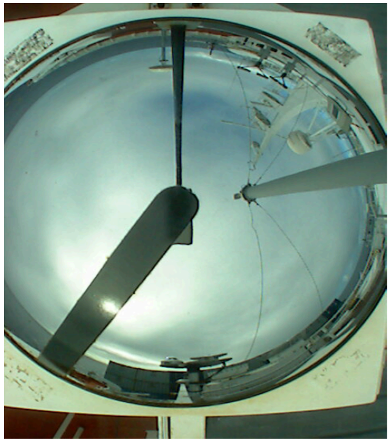
$$I(t,\lambda) = a(t)\, I(t_{\mathrm{cloudy}},\lambda) + b(t)\, I(t_{\mathrm{clear}},\lambda)$$

t is between t_{cloudy} and t_{clear}

$$I(t,\lambda)/I(t_{\mathrm{clear}},\lambda) = a(t)\, I(t_{\mathrm{cloudy}},\lambda)/I(t_{\mathrm{clear}},\lambda) + b(t)$$

for each time t: $y(\lambda) = a\, x(\lambda) + b$; a *is a slope* ; b *is an intercept*

Checking spectral-invariant hypothesis



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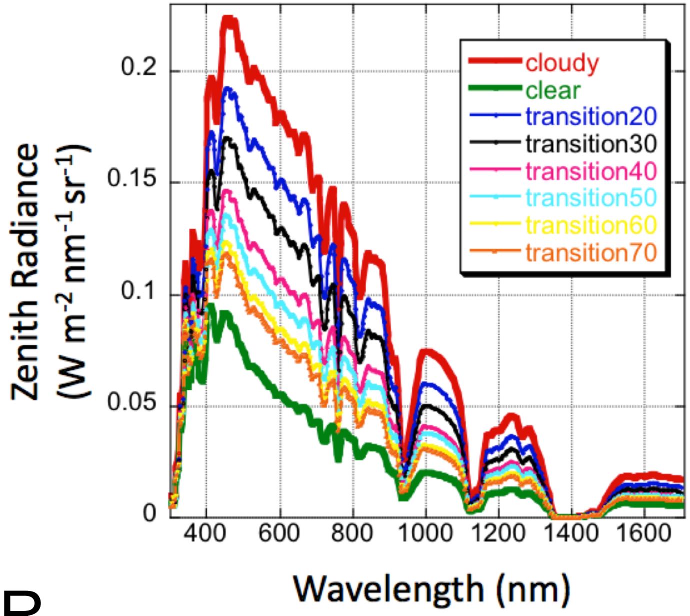
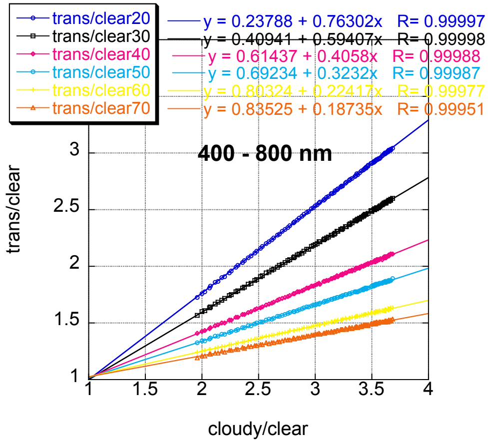


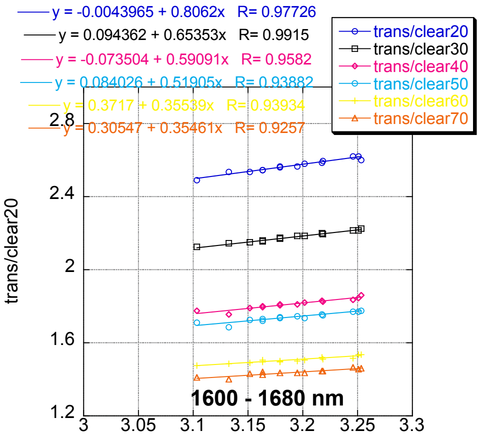
VIS



Ratio-to-clear

Cloudy-to-clear

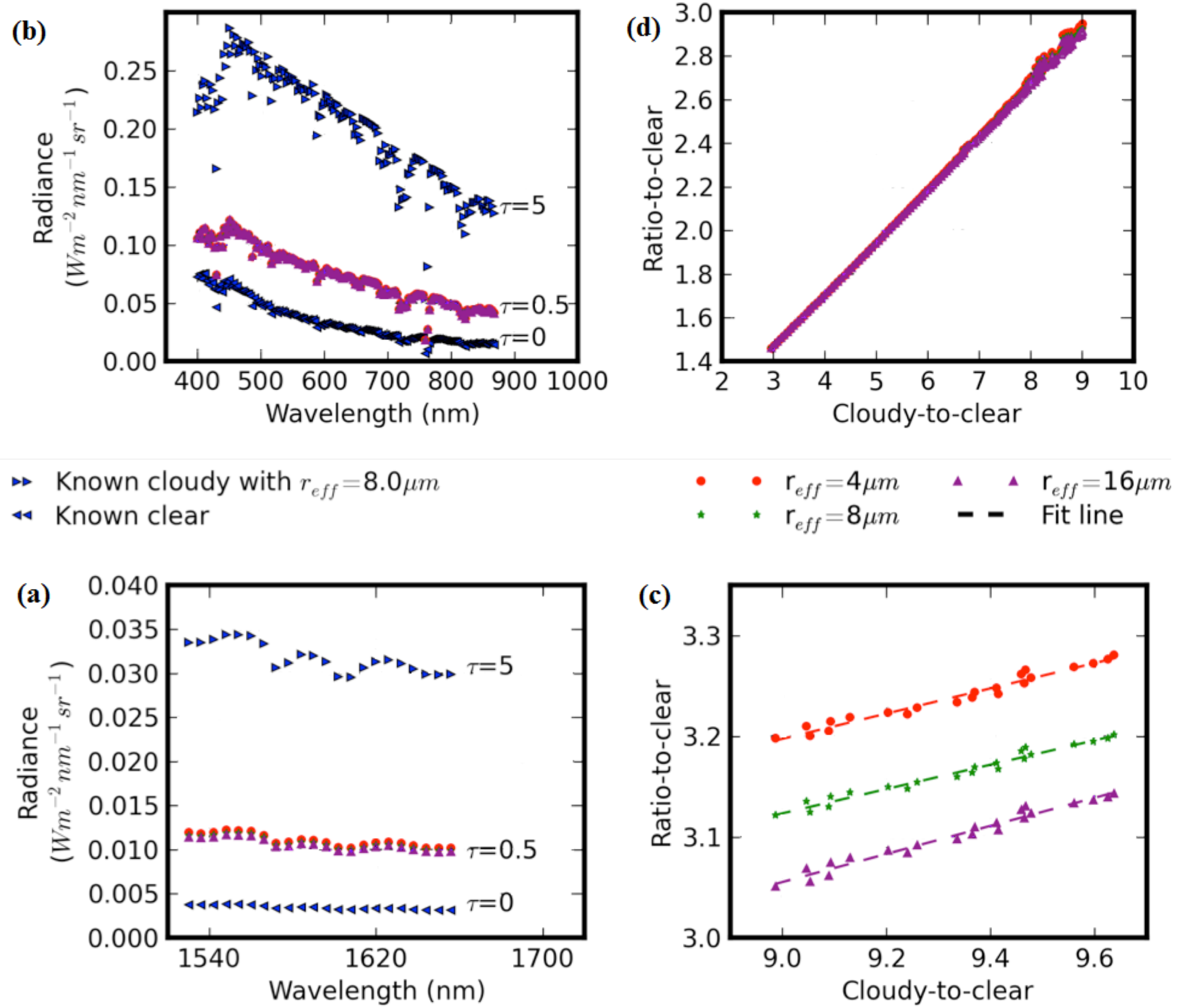
NIR



Ratio-to-clear

Cloudy-to-clear

SBDART simulations



VIS

NIR

The Main Properties of Spectral-Invariant Approach

- *Slope a(t) and intercept b(t)* are ***spectrally invariant*** and depend only on the adjacent **cloudy and clear sky** properties (Marshak et al., 2009).

- **Weak sensitivity** to the **aerosol** and **surface** spectral properties due to normalizing the spectrum of transition zone by the known clear-sky spectrum (Chiu et al., 2010).

- It uses spectra of ***ratios-to-clear*** that are much more robust than spectra themselves (Yang et al., 2016).

- Two spectral regions are selected: **VIS** and **NIR**. **Slope in the VIS** is ***positively*** correlated with COD. **Intercept in the NIR** spectral region is ***negatively*** correlated with cloud droplet size (Yang et al., 2019).

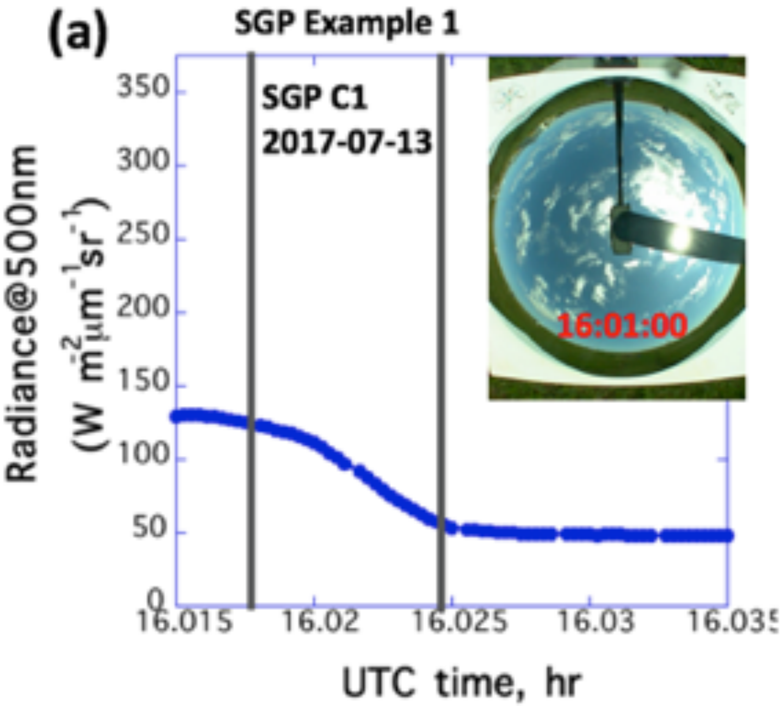
Data

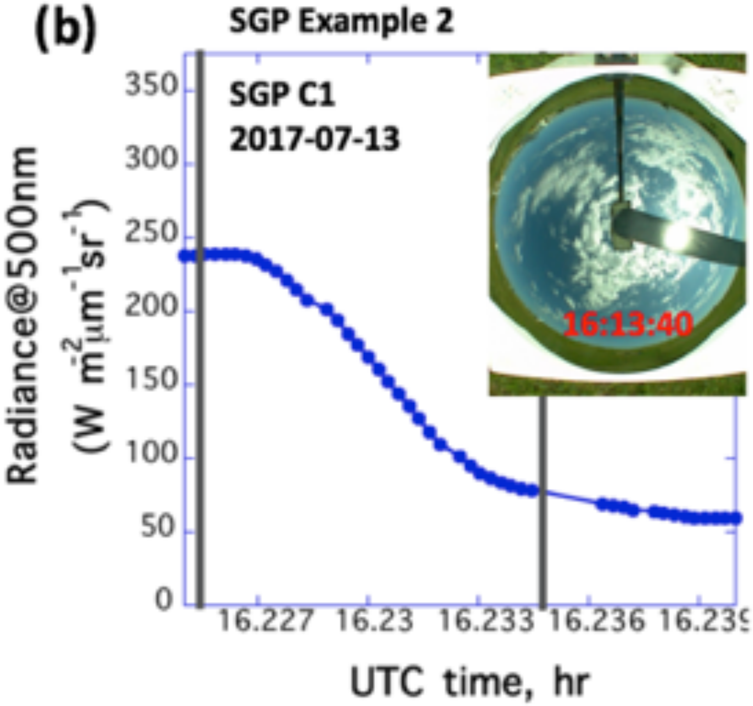
- **SASZe** radiance measurements at the SGP C1 site in July of 2014 and 2017 and during the MAGIC campaign in July, 2013.

- Spectral invariance properties of VIS (400 - 870 nm) and near-IR bands (1530 - 1660 nm) at their highest sampling frequency (1 Hz).

- Total Sky Imager (**TSI**) and **Ceilometer** were also used for assisting in selection the transition zones.

Two examples from SGP

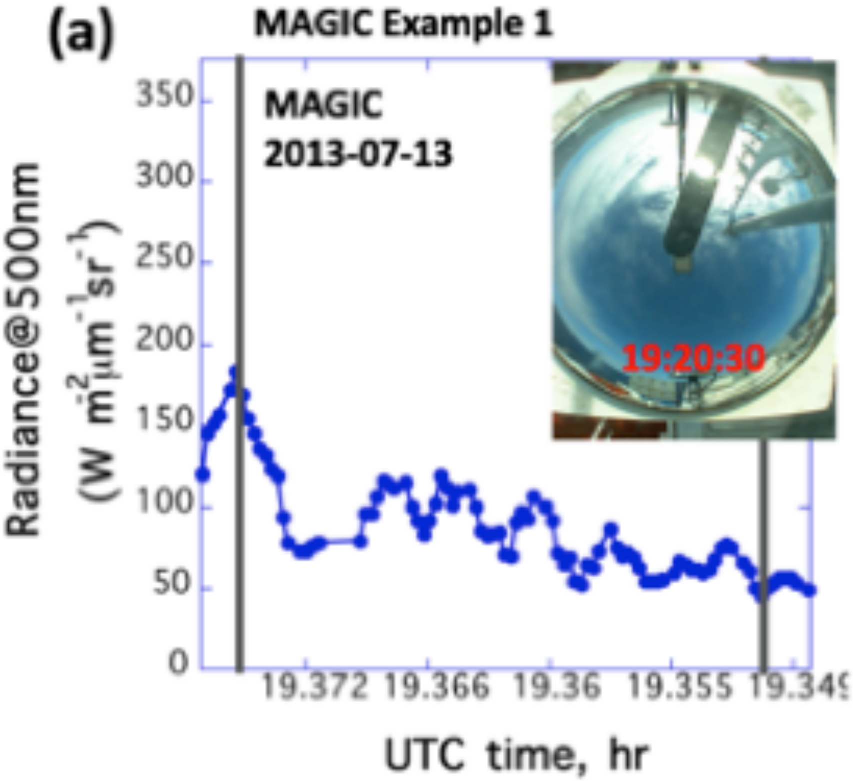


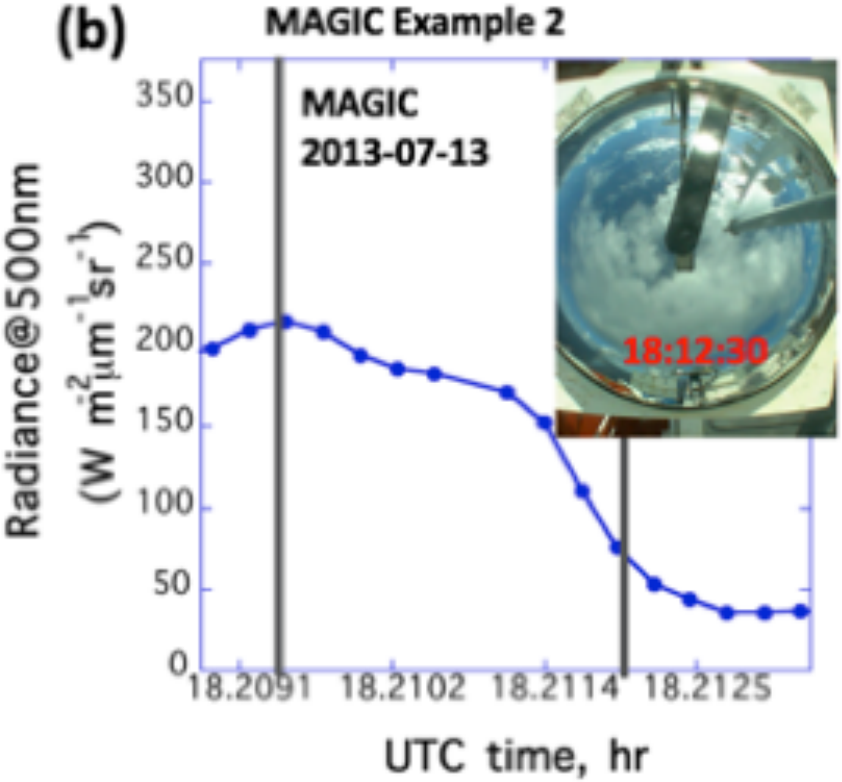


The transition zones (TZ) are between grey vertical lines.

The sizes of TZ are about 100 - 200 m assuming the cloud moving speed is ~5 m/s.

Two examples from MAGIC





Conclusions

- Spectral invariant method is **valid** for studying the cloud edge properties over both **land** and **ocean** areas:
  - the **slope** of the **VIS** band is **positively** correlated with τ.
  - the **intercept** of the **NIR** band has a high **negative** correlation with r_{eff} even without the exact knowledge of τ.
- Results of 22 cases from SGP and MAGIC suggest that while τ **decreases** during the cloudy-to-clear transition in all cases, the **decreasing trend of** r_{eff} **is much more significant in SGP** (over land) **than at MAGIC** (over ocean).
- These observational results support theoretical simulations of mixing processes by Pinsky and Khain, 2018

Thank you!