The impacts of 3D radiative transfer effects on cloud radiative property simulations and retrievals

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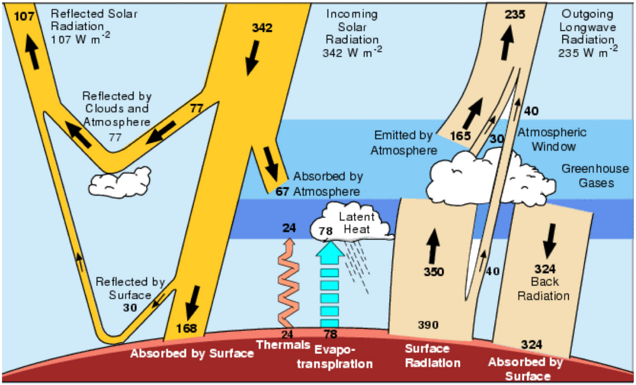
Outline

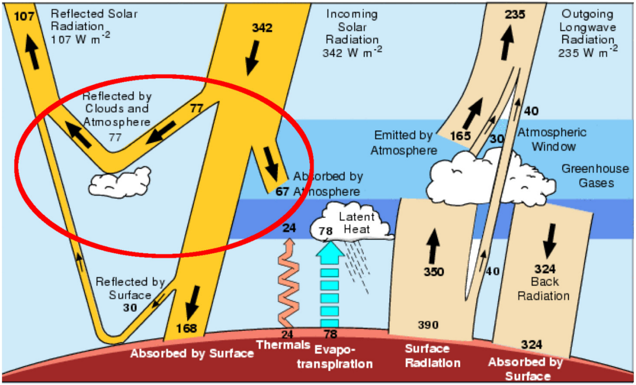
- Background-Why is radiative transfer important?
- Motivation-What are some issues with radiative transfer?
- 1D Examples
- MODIS data analyzing
- Surrogate cloud generation
- 3D radiative transfer simulation
- Future work and discussion

What happens to the radiation from the sun?



Trenberth et al. 2009 BAMS

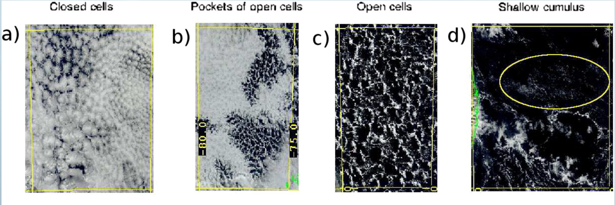
Here we will study cloud effects.



Trenberth et al. 2009 BAMS

Effects of Clouds

- Cooling effect: clouds reflect part of the incoming solar radiation back to space, which cools the climate.
- Warming effect: cloud and aerosol particles absorb the outgoing radiation from earth and re-emit at lower temperature, which warms the climate.



Stechmann & Hottovy 2016

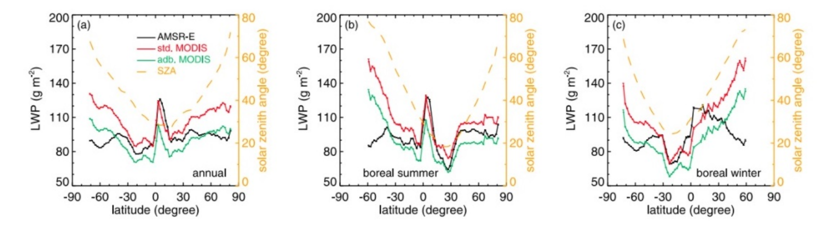
Why study radiation?

- Goal of solar radiation transport studies: track radiant energy entering at the top of the Earth's atmosphere.
- Climate studies: rely on accurate information on cloud properties and their spatial and temporal variation.
- Radiative Transfer Models play an important role in observed radiances of clouds.
  - Satellites measure solar radiation that clouds reflect. Current retrieval techniques are 1D.
  - Cloud horizontal inhomogeneity can induce net horizontal transfer of radiation that is neglected by the one-dimensional models on which retrievals are based.

Effects

3D radiative effects cause a wide variety of problems in the retrievals (solar elevation, cloud structure, and satellite resolution, etc).

- Causes shadows/illumination



Source: Seethala and Horváth 2009

Goal

Goal of our study:

Investigate 3D radiative transfer effects on the cloud property retrieval from satellite remote sensing, including COT, CER and LWP. The 3D effects would varies for different latitude and season(with different solar zenith angles)

Three parts:

- Analyze MODIS data, and understand cloud structure, through power spectrum, etc
- Generate synthetic clouds according to satellite observation
- Run 3D and 1D radiative transfer models, and evaluate the possible influence of the illuminating and shadowy pixels in cloud property retrieval

RT Method

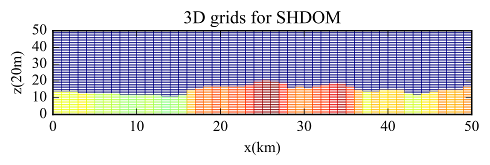
SHDOM:

(Spherical Harmonics Discrete Ordinate Method)

- Discretize the whole 3D spatial computational domain
- Store integration coefficients for each grid

Features:

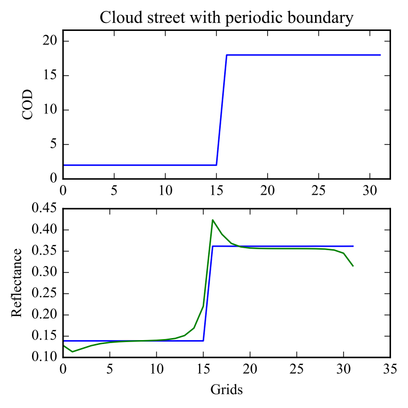
- Supports 1D, 2D, 3D
- Polarized or unpolarized
- Monochromatic or broadband
- Collimated solar or thermal emission
- Boundary condition: periodic or open
- Adaptive grids



Proof of concept

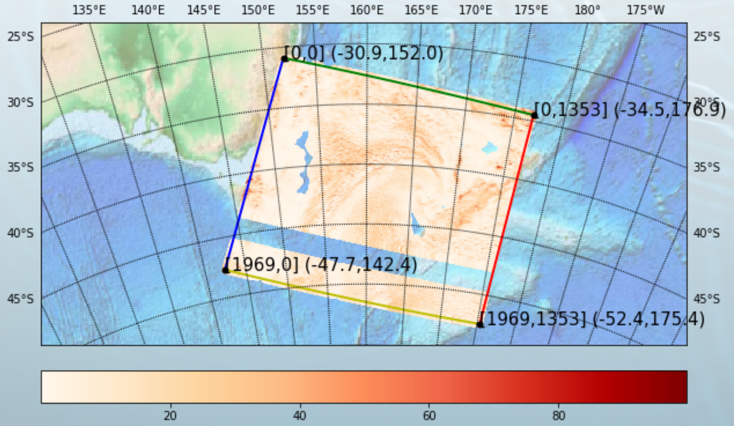
Step cloud study:

- Solar zenith angle of 60 degree.
- Periodic boundary condition.
- Both illuminating and shadowy effects are shown.



MODIS Data Analysis

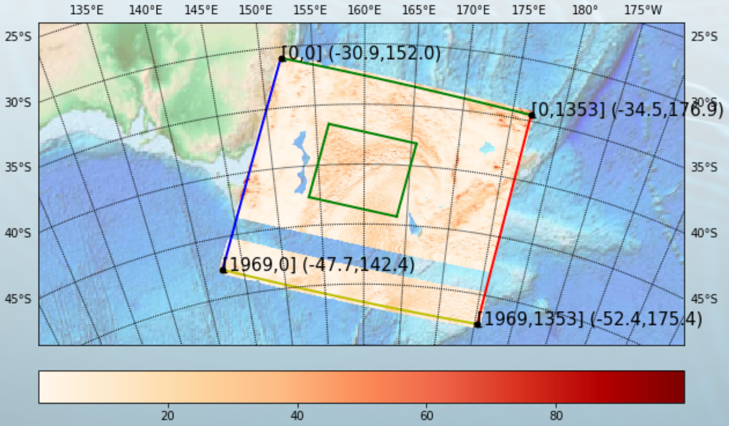
Obtain cloud field parameters from MOD06 file in Nov 1.2000



The graph shows the COT heat graph for the granule file MOD06_L2.A2000306.2325.006.2014297154828.hdf. It can be seen from the graph that there is an entire band of the granule file with missing values for COT. The granule file is selected such that the solar zenith angles are around 30 degrees, $\Theta \approx 30^{\circ}$, for its central area. In the granule file, the area surrounding the 40°S latitudes satisfies the above requirement for low zenith angles.

MODIS Data Analysis

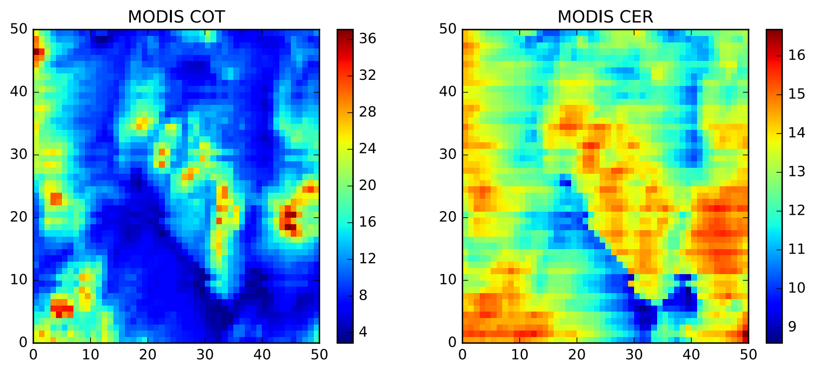
Cut cloud fields of $50km \times 50km$ from MOD06 file in Nov 1.2000



The graph shows how to cut the COT values of regions with dimension of $50km \times 50km$ from the granule file MOD06_L2.A2000306.2325.006.2014297154828.hdf. All the $50km \times 50km$ regions are selected around 40°S latitudes form the green box. The green box covers a region of dimension $700km \times 350km$. The MOD06 file contains many missing values. We only retrieved 37 $50km \times 50km$ regions without missing values for COT or CER.

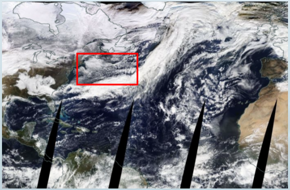
MODIS Data Analysis

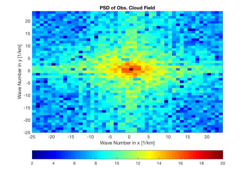
Example from 37 cloud scenes:
Cloud Optical thickness (COT)
Cloud effective radius (CER)

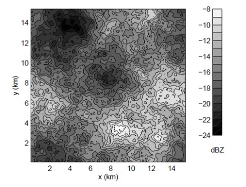


Surrogate Cloud Model

Surrogate cloud model takes observational statistics, then generates a cloud field with those statistics.







MODIS Clouds $\Longrightarrow$ Statistic $\Longrightarrow$ Cloud field

Allows us to sample many different cloud fields with similar properties.

Power Spectral Density

What statistic should we use?

- Have clouds with similar spatial structure.
- Preserve some mean features.
- Similar variance.

Power Spectral Density

$$S(\omega) = |\hat{\tau}(k_x, k_y)|^2$$

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Power Spectral Density

$$S(\omega) = |\hat{\tau}(k_x, k_y)|^2$$

$$\text{Energy} = \sum_{x,y} |\tau(x,y)|^2 = \sum_{k_x, k_y} |\hat{\tau}(k_x, k_y)|^2$$

by Parseval's theorem.

Advantages of PSD

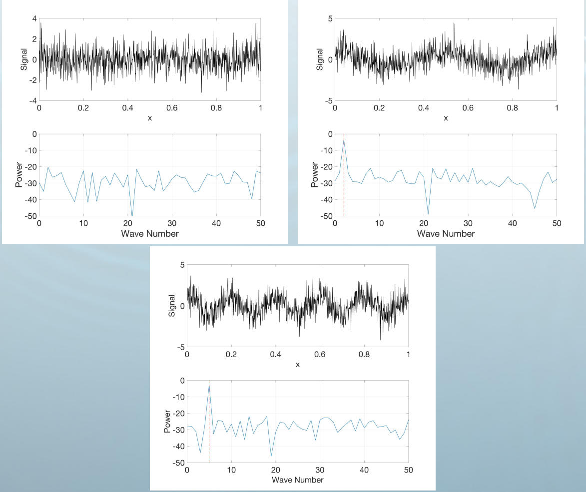
- Preserve mean cloud optical thickness (COT).
- Same variance of COT.
- Can be extended to finer resolutions.
- Spatial structure encoded in PSD.

Power Spectral Density (PSD)

$$S(\omega) = |\hat{\tau}(k_x, k_y)|^2 = |\widehat{\tau(x, y)\tau^*(x', y')}|$$

1D example

Random Noise vs. $cos(2\pi[2t])$ vs $cos(2\pi[5t]))$



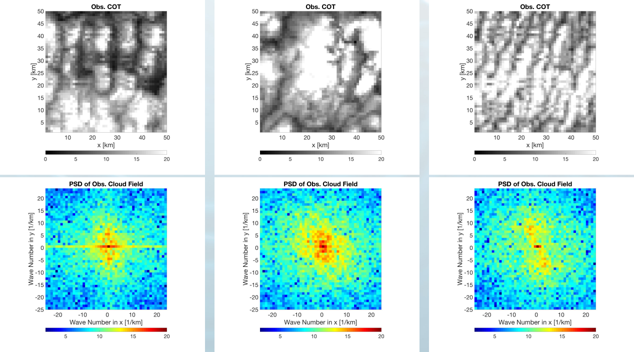
Model

- Fourier Cloud Field (Hogan and Illingworth 1999) “Cloud fields were generated by calculating the inverse 2D Fourier transform of synthetic matrices containing wave amplitudes consistent with energy at the various scales indicated by the one dimensional spectrum.”
- **Algorithm:**

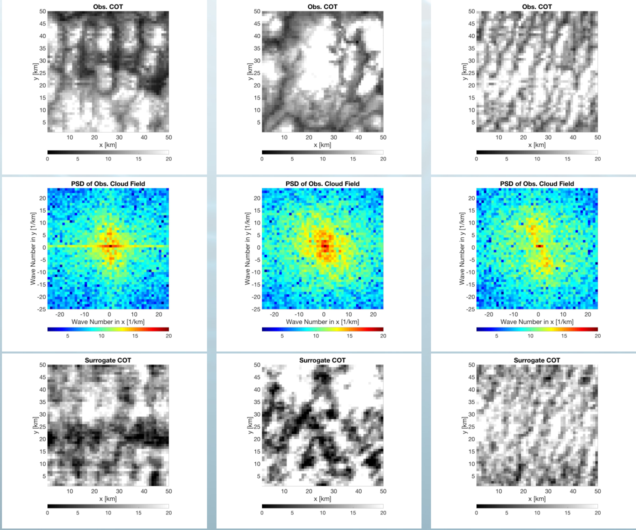
1. Input: Power spectrum of COT
2. Calculate the Fourier coefficients ($\sqrt{PSD}$)
3. Create random phase shift (to generate diff. cloud fields)
4. Satisfy symmetric condition of FT for real values.

$$\hat{\tau}(-k) = \hat{\tau}(k)^*$$

Surrogate Clouds

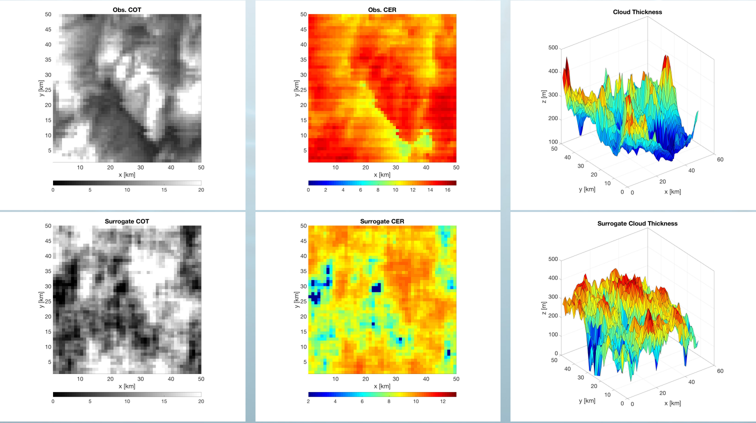


Surrogate Clouds



RT Example

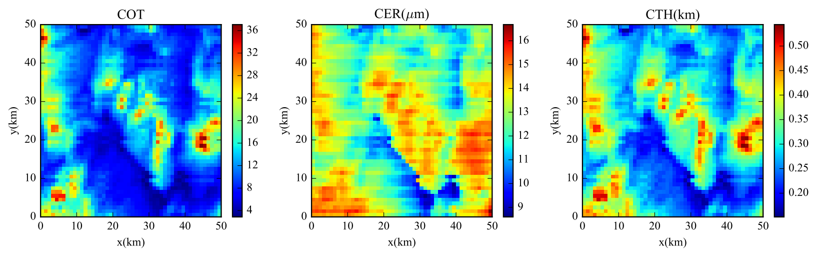
Use atmospheric relationships to derive cloud height and cloud effective radius (CER) from COT.

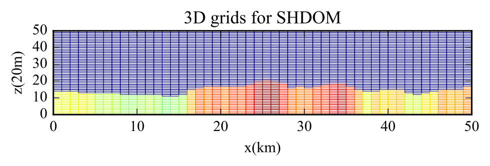


Radiative Transfer Method

Build 3D cloud:

- Based on MODIS observation and surrogate cloud.
- COT and CER, CTH varies in horizontal directions.

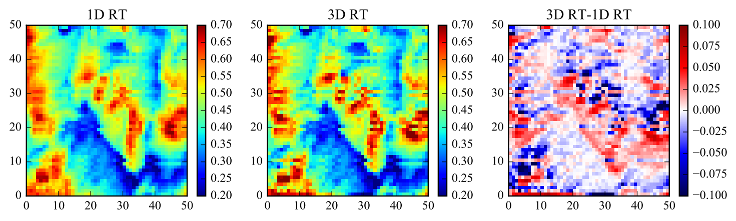




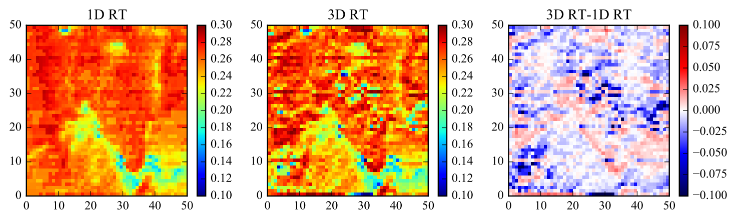
Radiative Transfer Method

Solar zenith angle: 60°

Reflectance (0.86μm):

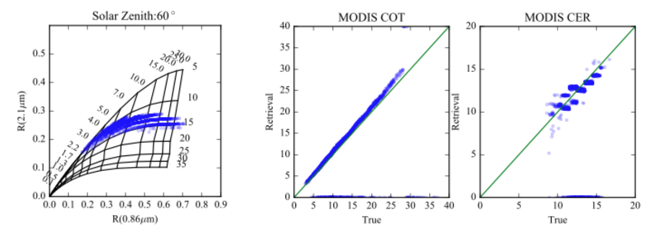


Reflectance(2.1μm):

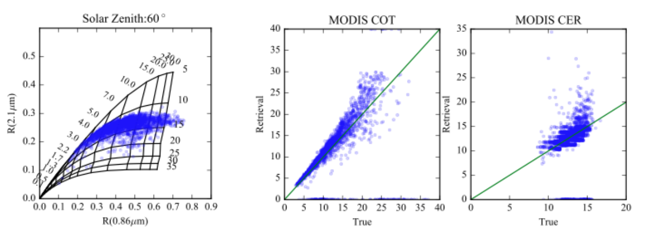


Radiative Transfer Method

COT/CER retrieval(1D RT)

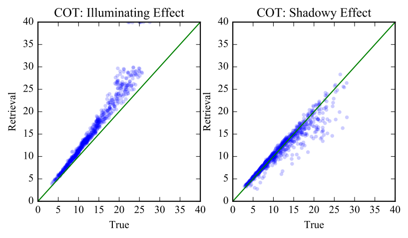


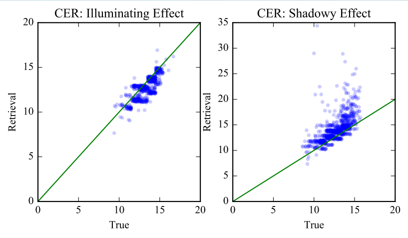
COT/CER retrieval(3D RT)



Radiative Transfer Method

Evaluate illuminating and shadowy pixels:

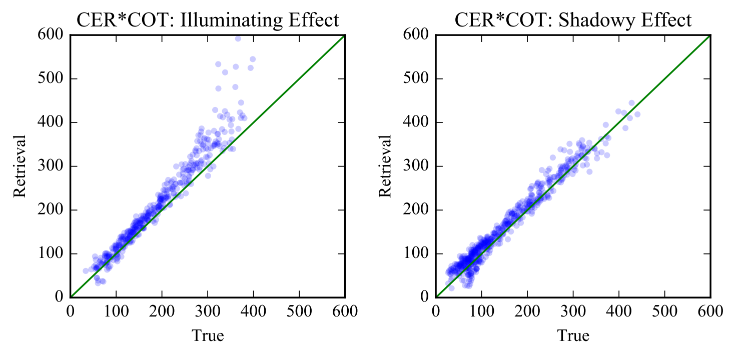




Radiative Transfer Method

Liquid water path:

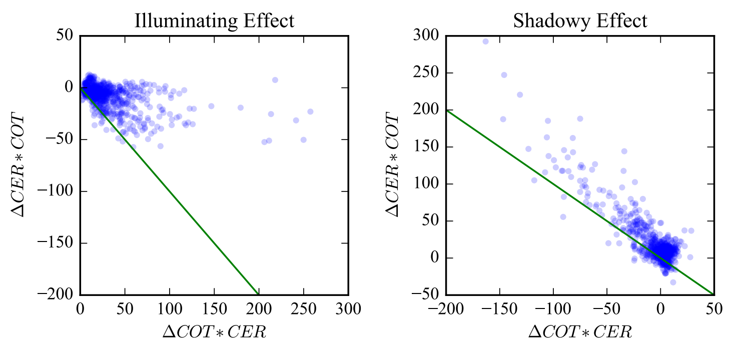
- $LWP = 4\rho_w/(3Q_e)COT \times CER$ (Seethala et al 2010)
- LWP is over estimated for both shadowy and illuminating pixels in average.



Radiative Transfer Method

Liquid water path changes:

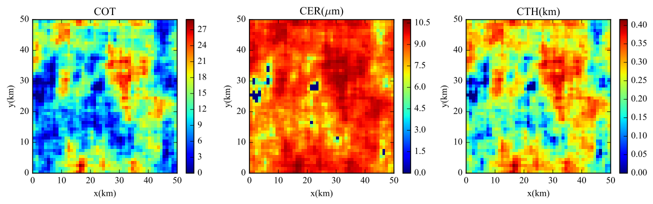
- $\Delta LWP \sim \Delta COT \times CER + \Delta CER \times COT$
- Illuminating pixel: ΔCOT effects is stronger than ΔCER effects
- Shadowy pixel: ΔCER effects is stronger than ΔCOT effects

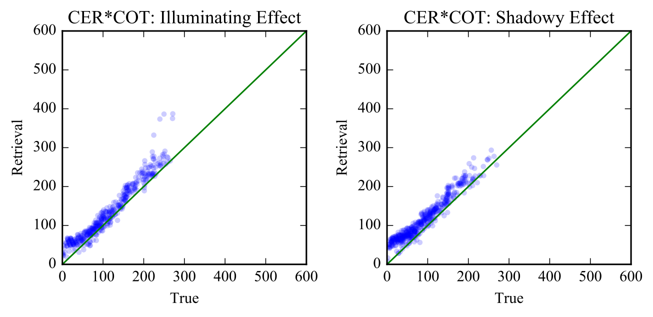


Radiative Transfer Method

Liquid water path:

- Surrogate cloud shows similar results.





Conclusion

We have built a workflow to study the 3D cloud effects:

- Analyzed MODIS data, and understand cloud structure, through power spectrum, etc
- Generated surrogate clouds according to satellite observation.
- Evaluated the influence of the 3D cloud structure in cloud property retrieval by comparing the 3D and 1D radiative transfer simulation.

Future work

- The current 3D RT study ignored the cloud structure within 1km. Using surrogate clouds, we could increase the resolution.
- Explore more cloud scenes with various domains and structures.
- Identify cloud structures where illuminating/shadowing effects are most prominent.
- Can these cloud structures be classified by their power spectral density?