



CERES Science Team Meeting, NASA GISS, October 17–19th, 2023

Zonal Cloud Trends Observed by CALIPSO-CloudSat and MODIS

Seung-Hee Ham¹, Norman Loeb², Seiji Kato², Tyler Thorsen²,
Aiko Voigt³, and David Winker²

¹Science Systems and Applications, Inc. (SSAI), Hampton, Virginia, USA

²NASA Langley Research Center, Hampton, Virginia, USA

³Department of Meteorology and Geophysics, University of Vienna, Vienna, Austria

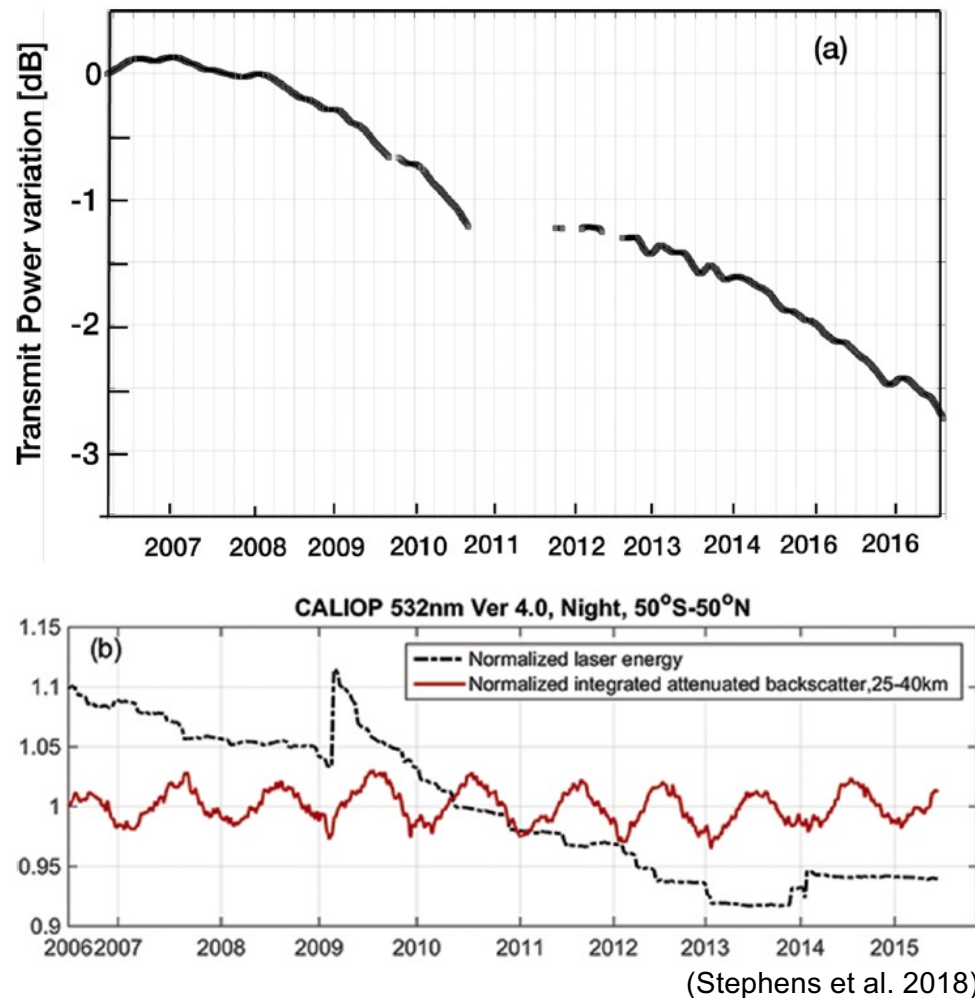
Background

- CALIPSO CALIOP and CloudSat CPR active sensors can detect cloud vertical structures directly, which is an advantage compared to passive sensors such as MODIS.
- However, the long-term cloud study has been limited due to the short satellite record and calibration issues.

Scientific Question

- Can we obtain 10-year zonal cloud trends from CALIPSO and CloudSat?
- How are these CALIPSO-CloudSat zonal cloud trends compared with those from MODIS?

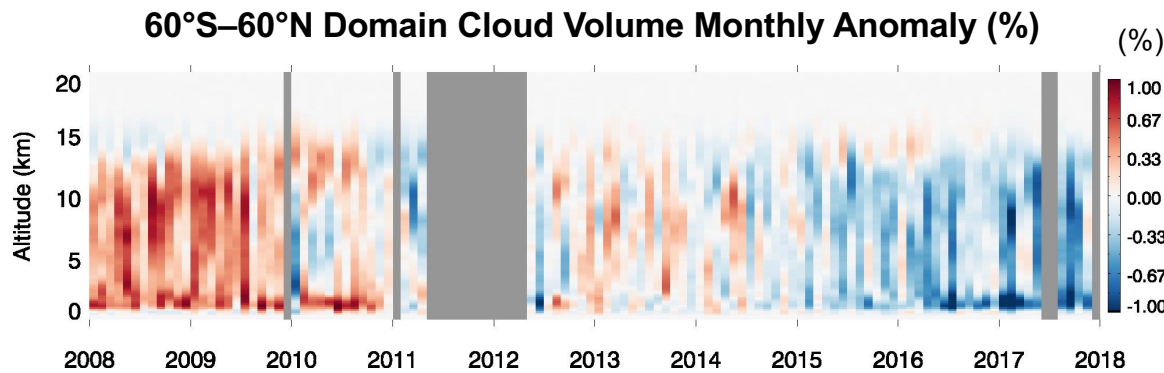
Potential Issues in CALIPSO and CloudSat Sensor Degradations



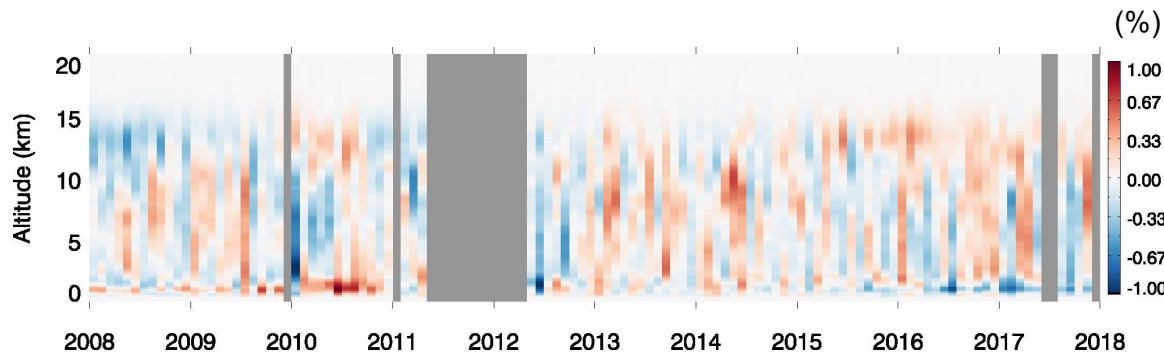
- The CPR sensor output power degraded over time, causing changes in minimum detectable radar reflectivity from -30 dBZ to -25 dBZ.
- CALIPSO has two redundant laser transmitters. The second laser replaced the first laser in March 2009, causing a sudden increase of laser energy and a rapid drop after that. The time series of the normalized backscatter remains stable but signal-to-noise ratio might have changed time to time.

Impact of CloudSat Sensor Degradation: A Threshold of Radar Reflectivity

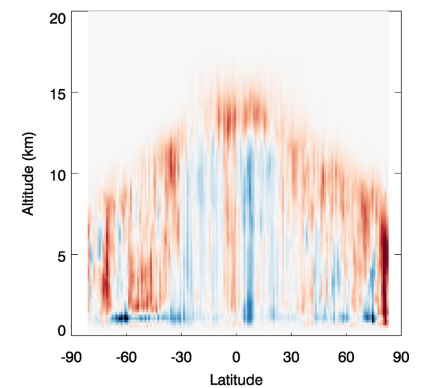
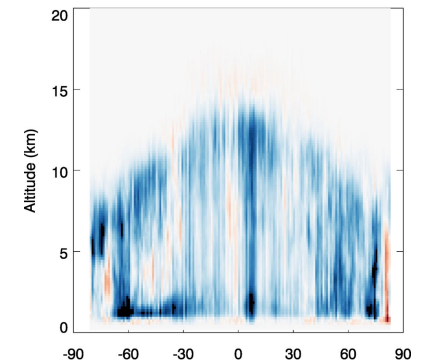
All CloudSat
Clouds



CloudSat
Clouds
with
 $Z \geq -25$ dBZ



2008-2017
Cloud Trend (% dec⁻¹)



-3.0 -2.0 -1.0 0.0 1.0 2.0 3.0
(% dec⁻¹)

- CPR degraded over time, causing a decreasing zonal cloud trend.
- An additional threshold of radar reflectivity (-25 dBZ) in selecting clouds effectively removes the artifact in decreasing cloud trend.

CALIPSO Clouds

- CALIPSO cloud information is from CALIPSO V4 Vertical Feature Mask (VFM) product.
- Cloud layers in CALIPSO VFM product are described using three parameters:

- 1. Horizontal averaging scales (HOR) used for cloud detections:**

The cloud can be detected from a single lidar beam (1/3 km), or spatial averaging of several numbers of lidar beams (1, 5, 20, or 80 km) to increase signal-to-noise ratio. A more tenuous cloud layer requires a larger HOR for detections.

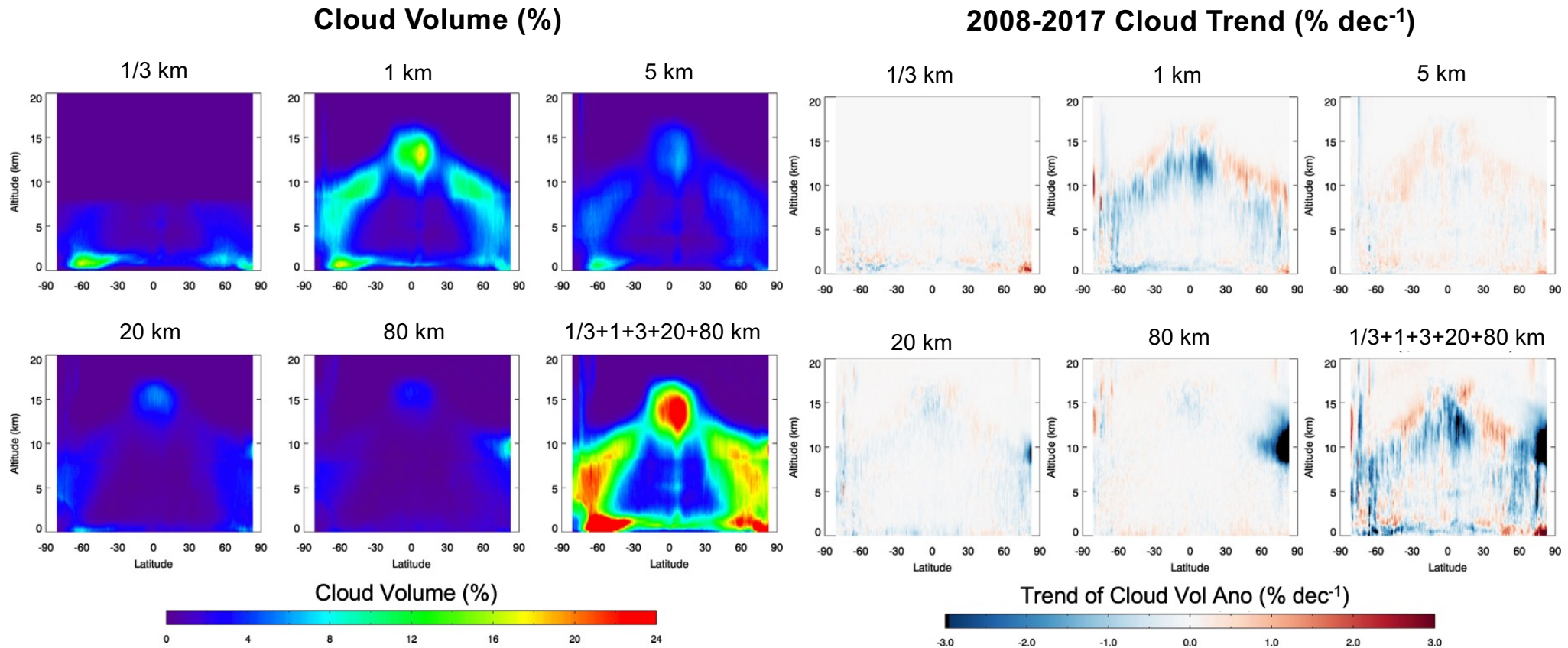
- 2. A confidence level (i.e., cloud-aerosol-discrimination; CAD score):**

A positive CAD score means clouds, and a negative value means aerosol. A high positive value means a higher confidence of clouds, and a smaller value means a larger chance of aerosol contamination in cloud detections.

- 3. Cloud optical depth (τ):**

CALIPSO CPRO 5km product provides cloud extinction profiles, which can be used to estimate layer cloud optical depth of each layer. Since MODIS often misses clouds with $\tau < 0.3$ (Kato et al. 2019), a filtering method can be considered to exclude optically thin clouds in CALIPSO measurements.

Horizontal Scales of Spatial Averaging (HOR) for CALIPSO Cloud Detections

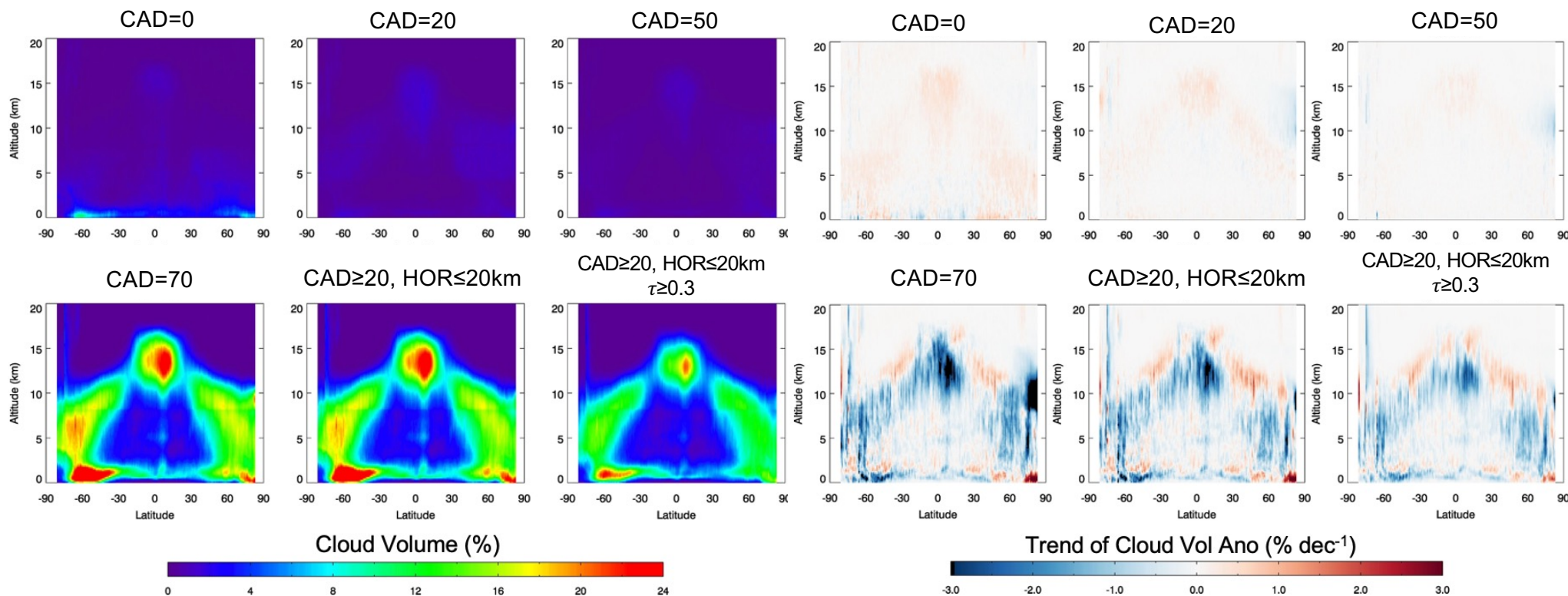


- CALIPSO lidar signals are spatially averaged to increase signal-to-noise (SNR) ratio for cloud detections.
- Most of clouds are detected from 1-km spatial averaging.
- A decreasing trend of 1-km clouds and an increasing trend of 5-km clouds.
- 80-km clouds appear over the Arctic stratosphere, showing a large decrease.

Confidence for CALIPSO Cloud Detections : CAD (Cloud-Aerosol Discrimination)

Cloud Volume (%)

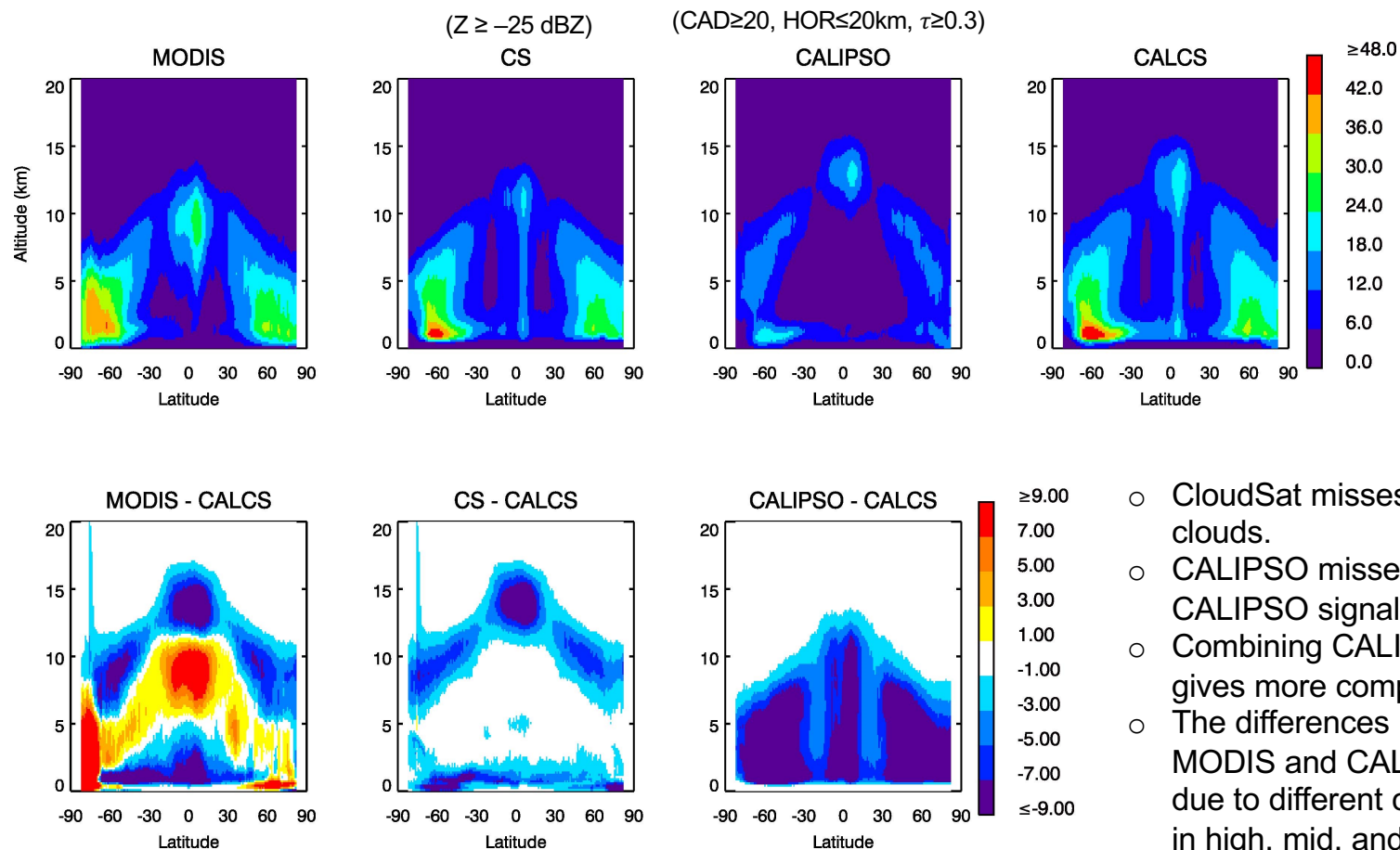
2008-2017 Cloud Trend (% dec⁻¹)



- Most of CALIPSO clouds are detected with a high confidence level (CAD = 70).
- Clouds with a low confidence level (CAD=0) seems to be mostly related to aerosol layers near surface.
- We can consider $CAD \geq 20$ and $HOR \leq 20$ km to minimize impact of aerosol and Arctic stratospheric clouds.
- Applying $\tau \geq 0.3$ further reduces a large decreasing cloud trend over the Tropics.

Combining CALIPSO and CloudSat to see more complete picture of cloud distributions

2008, Daytime

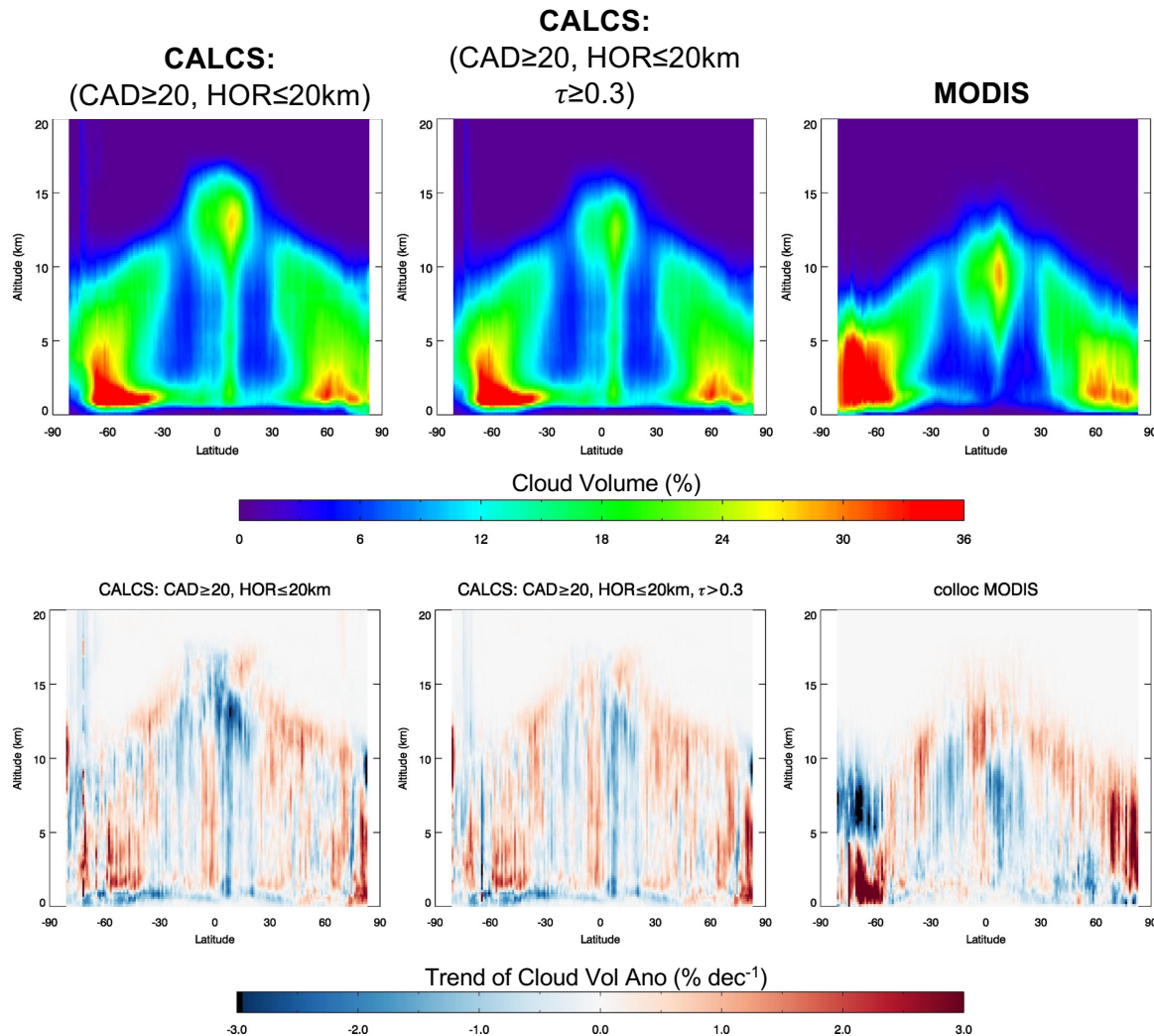


- CloudSat misses thin cirrus and low clouds.
- CALIPSO misses mid/low clouds when the CALIPSO signal is fully attenuated.
- Combining CALIPSO+CloudSat (CALCS) gives more complete picture of clouds.
- The differences in cloud amounts from MODIS and CALCS seem to be mostly due to different cloud heights. Differences in high, mid, and low clouds are compensating.

CALIPSO+CloudSat (CALCS) versus MODIS

Cloud Volume (%)

2008-2017 Trend (% dec⁻¹)

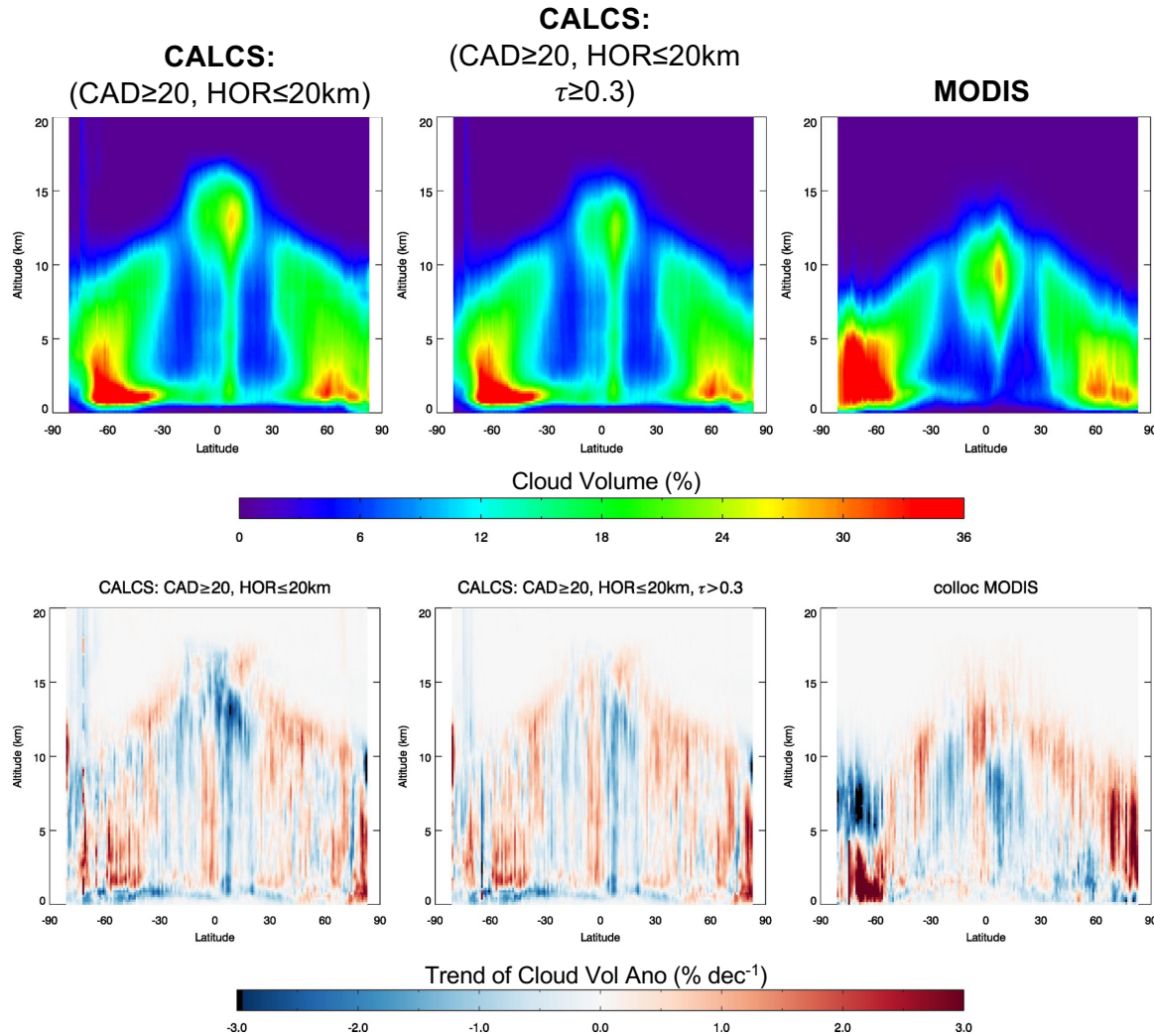


- CALCS trend with cloud optical depth (τ) filtering ($\tau \geq 0.3$) is better agreed with MODIS, compared to CALCS trend without τ filtering.
- Both CALCS and MODIS indicate an increase of uppermost clouds and a decrease underlying clouds over 60°S–60°N.
- Cloud altitudes in CACS and MODIS trends over the Antarctic are different: Probably due to uncertainties in MODIS cloud height retrievals in temperature inversion or skin temperature issues.

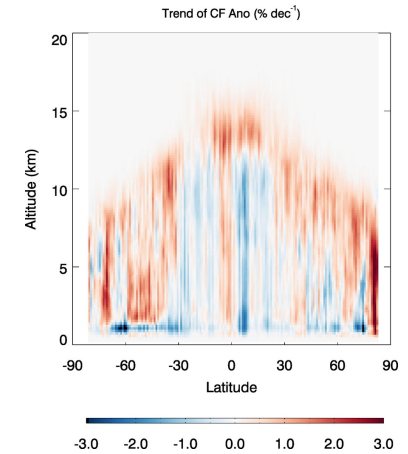
CALIPSO+CloudSat (CALCS) versus MODIS

Cloud Volume (%)

2008-2017 Trend (% dec⁻¹)



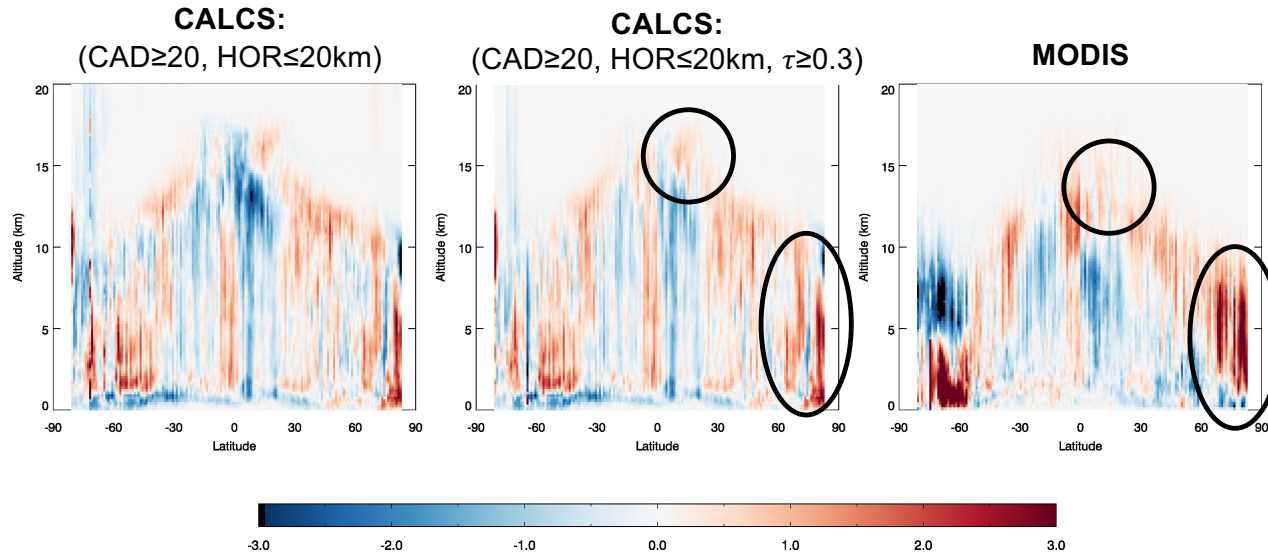
2008-2017 Trend
from CloudSat



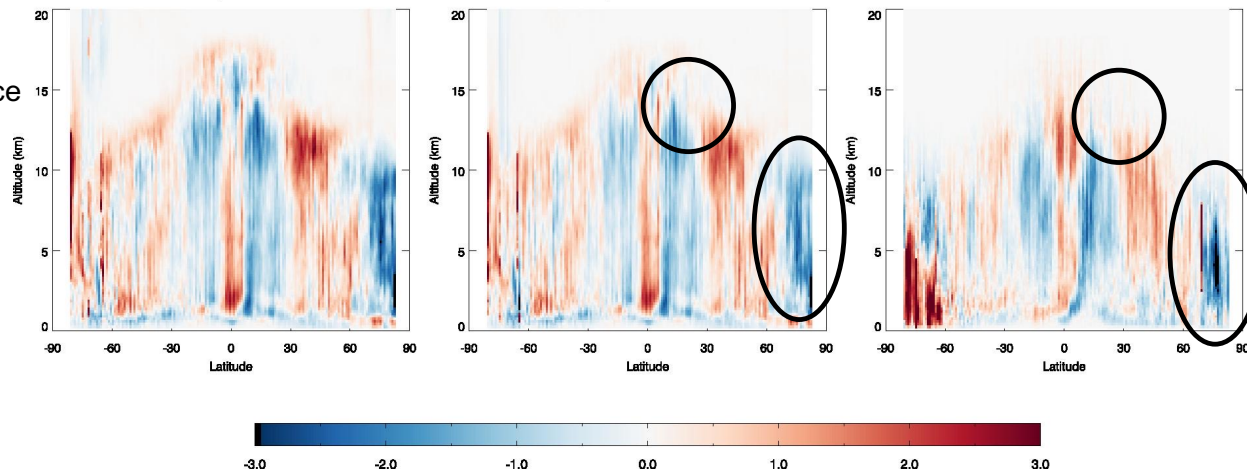
CloudSat trend is also comparable to MODIS or CALCS trends. However, it should be noted that significant amount of low clouds is missed by CloudSat.

Cloud Trends versus ENSO Signal

2008-2017
Cloud Trend
(% dec⁻¹)



ENSO Signal:
Cloud volume difference
between El Niño
(MEI $\geq$ +0.5)
and La Niña
(MEI $\leq$ -0.5) Periods



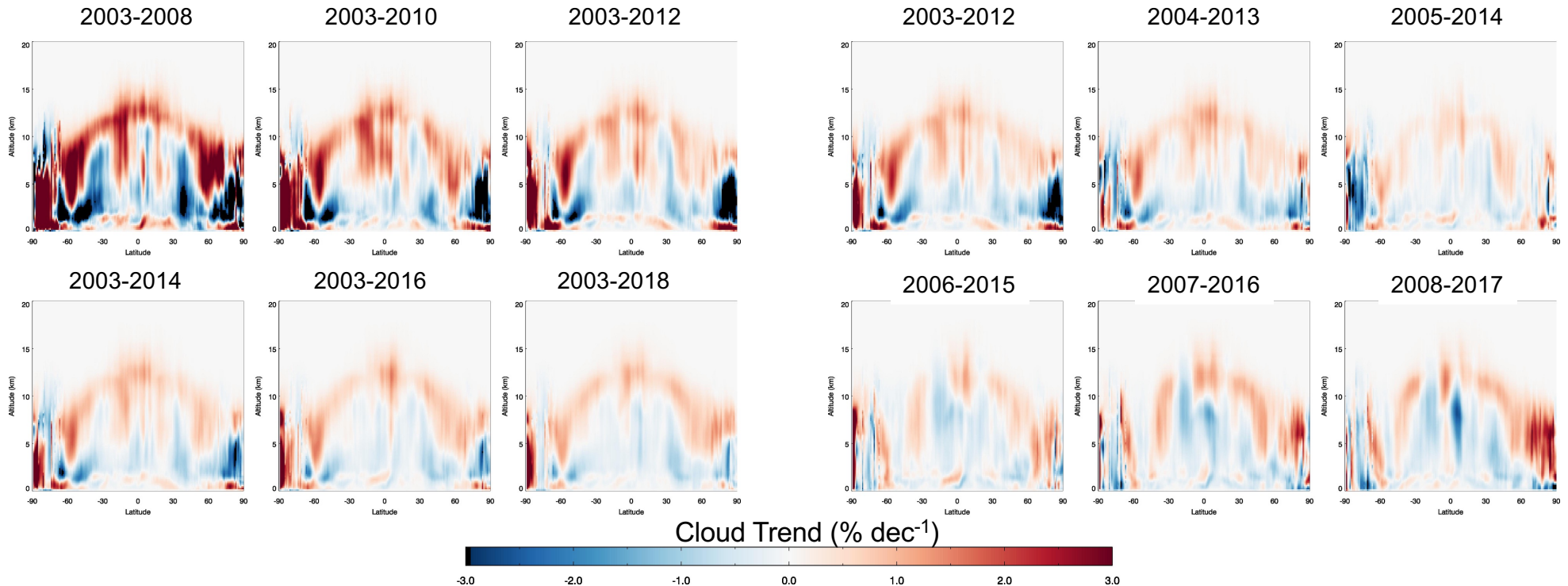
- While the positive cloud trend is noted in uppermost cloud layers in most of regions between 60°S–60°N, ENSO signal dose not show this feature.
- Over the Arctic, ENSO signal is negative, while the trend is positive.

Cloud Trends For Various Periods Using MODIS Aqua

Aqua MODIS, all sampling

Start Year Fixed as 2003

Length of Periods Fixed as 10 Years



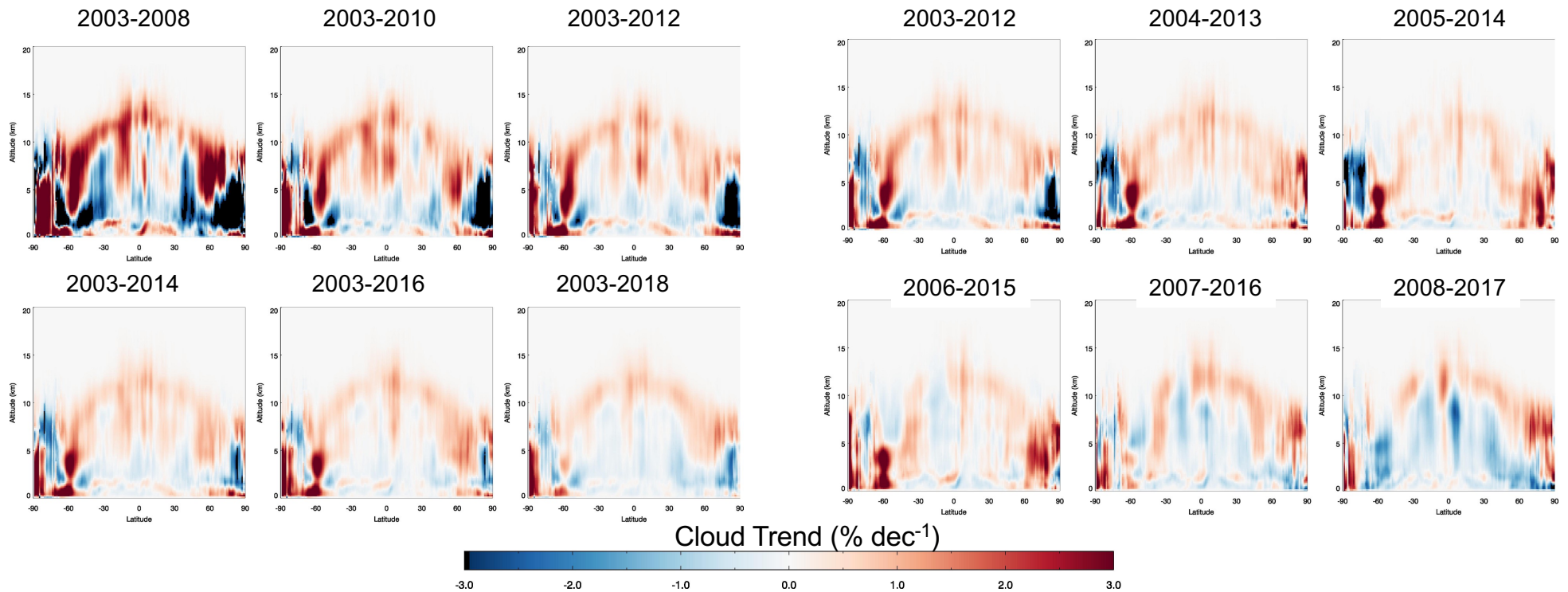
- An increase of uppermost cloud layer is more evident when the period of MODIS observation is extended.
- When the fixed length of the period as 10 years is considered, earlier period shows larger increase of uppermost cloud amounts than in later periods.

Zonal Cloud Trends For Various Periods Using MODIS Terra

Aqua MODIS, all sampling

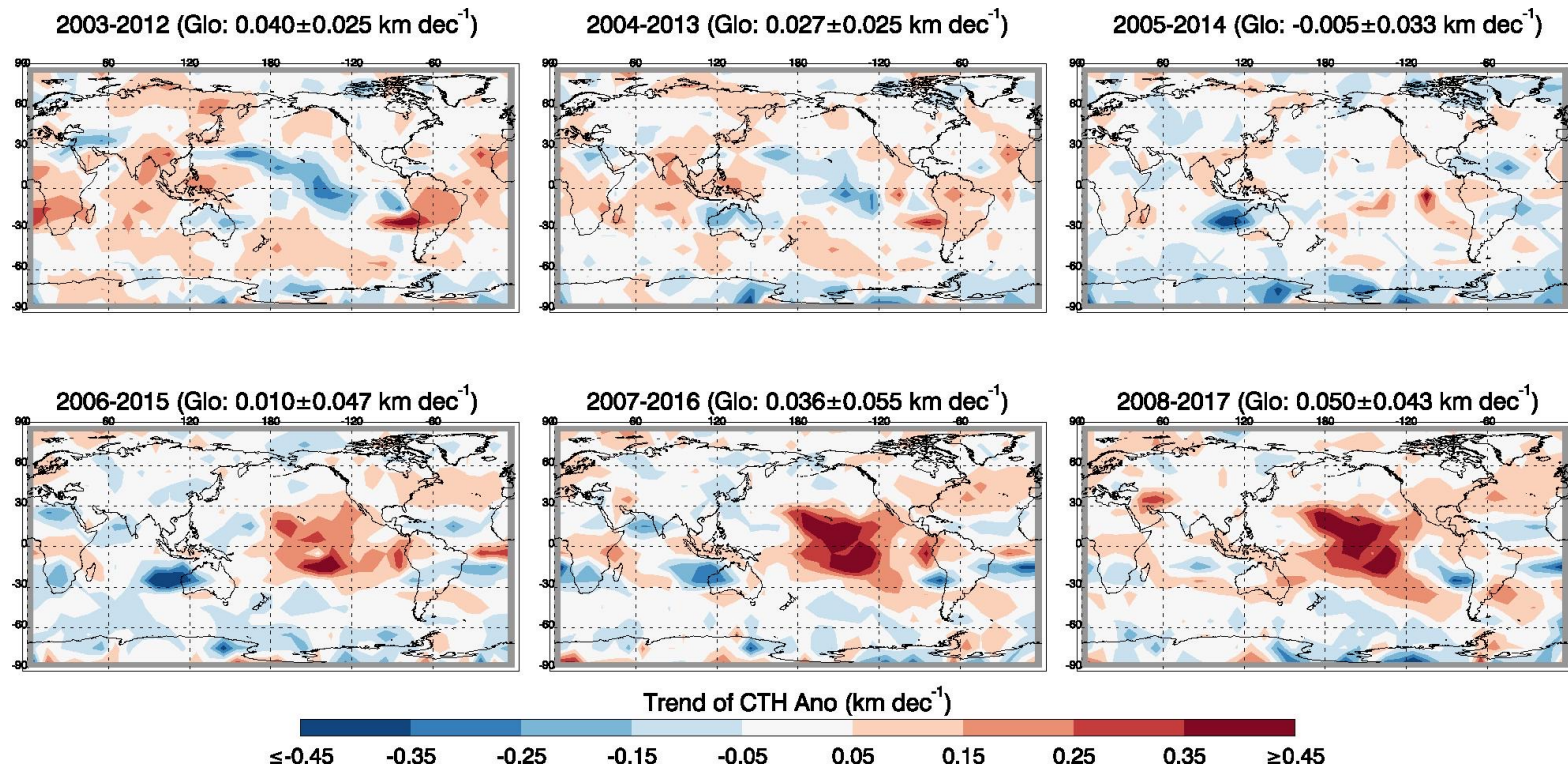
Start Year Fixed as 2003

Length of Periods Fixed as 10 Years



- Cloud trends from Terra Aqua is also very similar results to those from Aqua MODIS.

Where Did High Clouds Rise? (Aqua MODIS/ 10-yr Period)

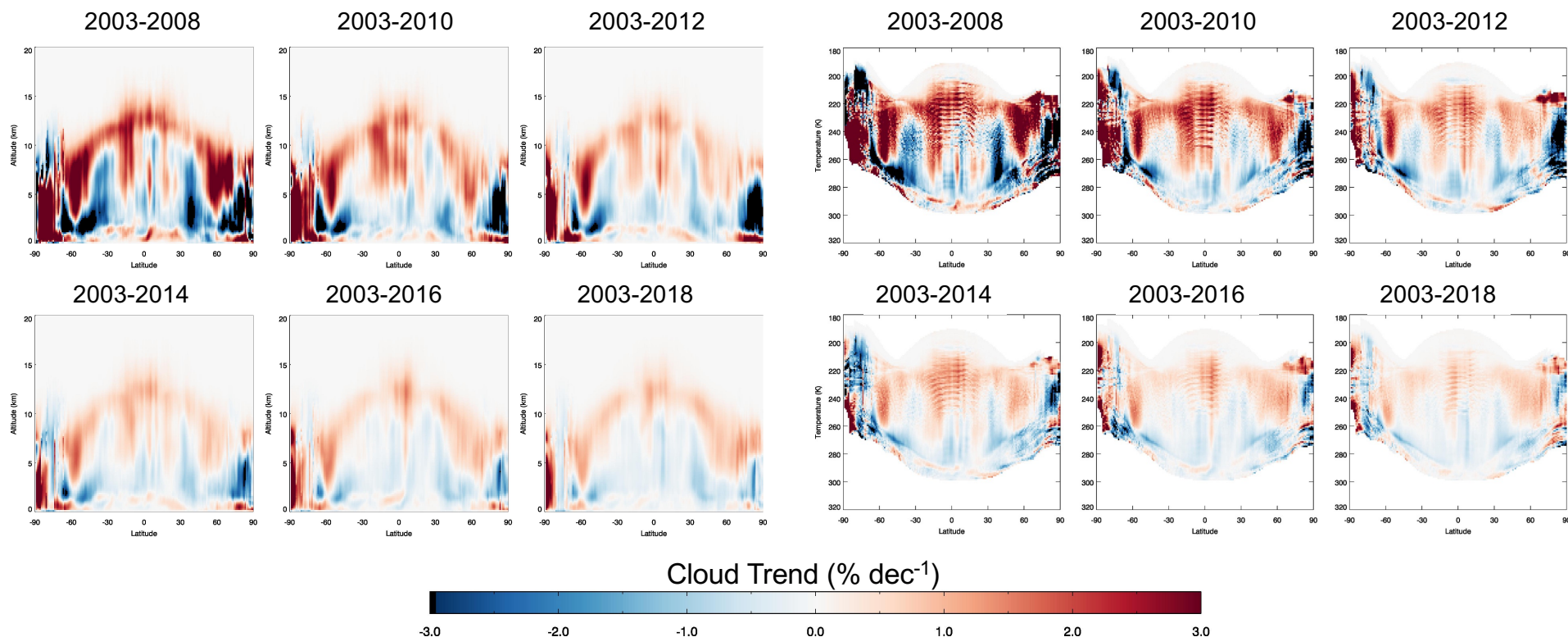


- High clouds are defined when the top is between 10 and 18 km. Then trends of the cloud top height (CTH) of high clouds are obtained for various periods. It seems that the location where high clouds rose vary time to time.

Would A Higher Cloud Bring A Cold Cloud Thermal Emission?

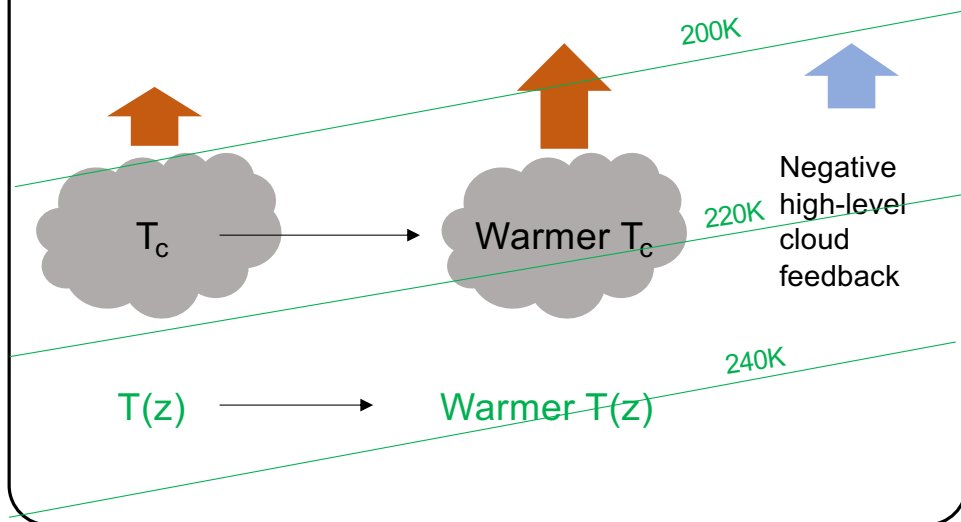
Aqua MODIS, all sampling

Start Year Fixed as 2003

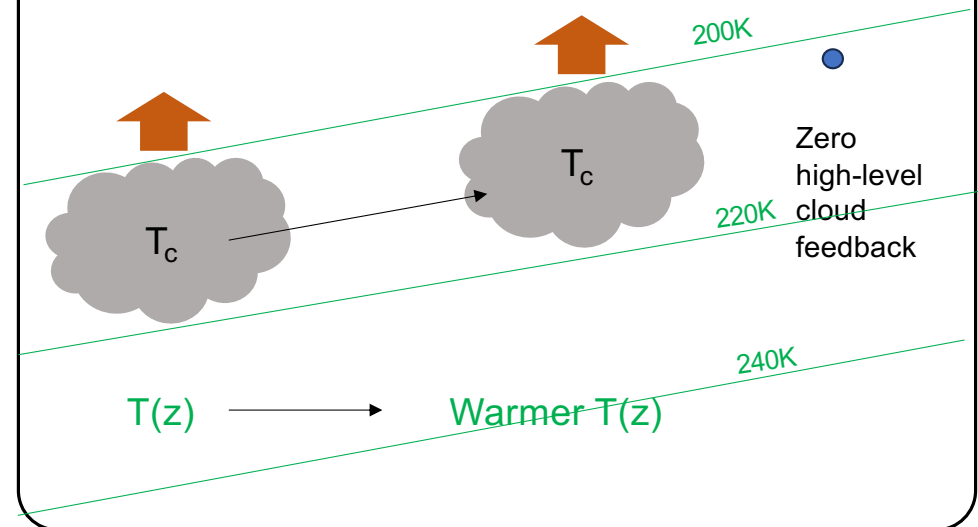


As the cloud top heights of uppermost cloud layers increased, cloud occurrences at colder temperature (220 K) increased as well. This implies a colder cloud emission, and positive cloud feedback.

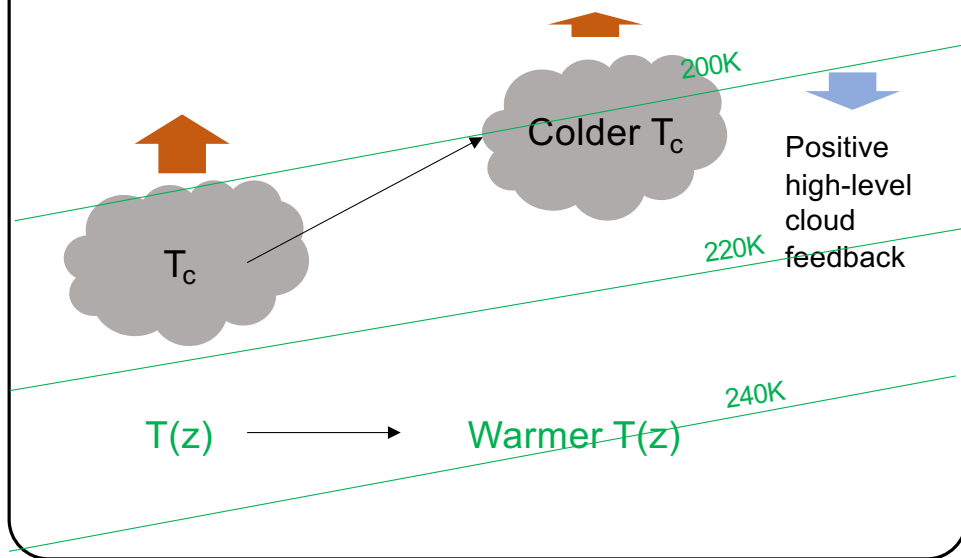
Fixed z_c under global warming



Fixed T_c under global warming (FAT hypothesis)

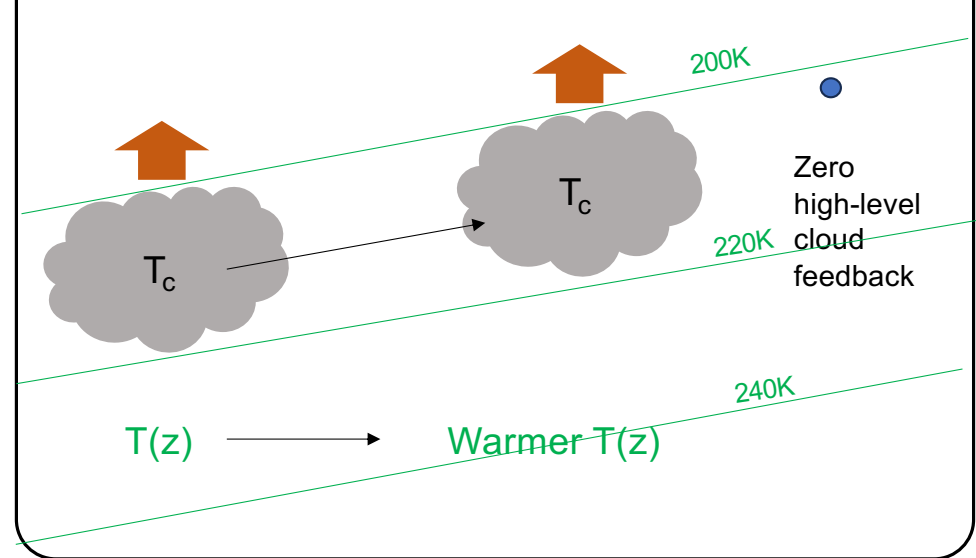


Higher z_c , colder T_c under global warming



"Early period of A-train Mission (Until ~2013)"

Fixed T_c under global warming (FAT hypothesis)



"Later period of A-train Mission (After ~2013)"

Summary

- CALIPSO and CloudSat give more detailed cloud vertical structures than passive MODIS sensors. However, it does not necessarily mean that those active sensors will give a more accurate cloud trends. Moreover, CALIPSO and CloudSat miss some of cloud layers.
- To mitigate the impact of sensor degradations, we additionally apply a threshold of CloudSat radar reflectivity ≥ -25 dBZ, which seems to remove artifacts in CloudSat cloud trends related to the CPR degradation. For CALIPSO clouds, a cloud condition of $\text{HOR} \leq 20$ km and $\text{CAD} \geq 20$ removes impacts of PSC and aerosols. CALIPSO clouds with $\tau > 0.3$ are considered to minimize the impact of CALIPSO signal-to-noise (SNR) ratio changes and to have more consistent comparison with MODIS cloud changes.
- When clouds detected by CloudSat+CALIPSO clouds are filtered for known sensitivity differences, trends agree well with MODIS cloud trends. The trends are partly explained by ENSO signal. Another factor is related to rising high clouds.
- The rising high clouds caused colder cloud temperatures, causing a smaller OLR, implying positive cloud feedback.