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

Zonal Cloud Trends Observed by CALIPSO-CloudSat (CALCS) and MODIS

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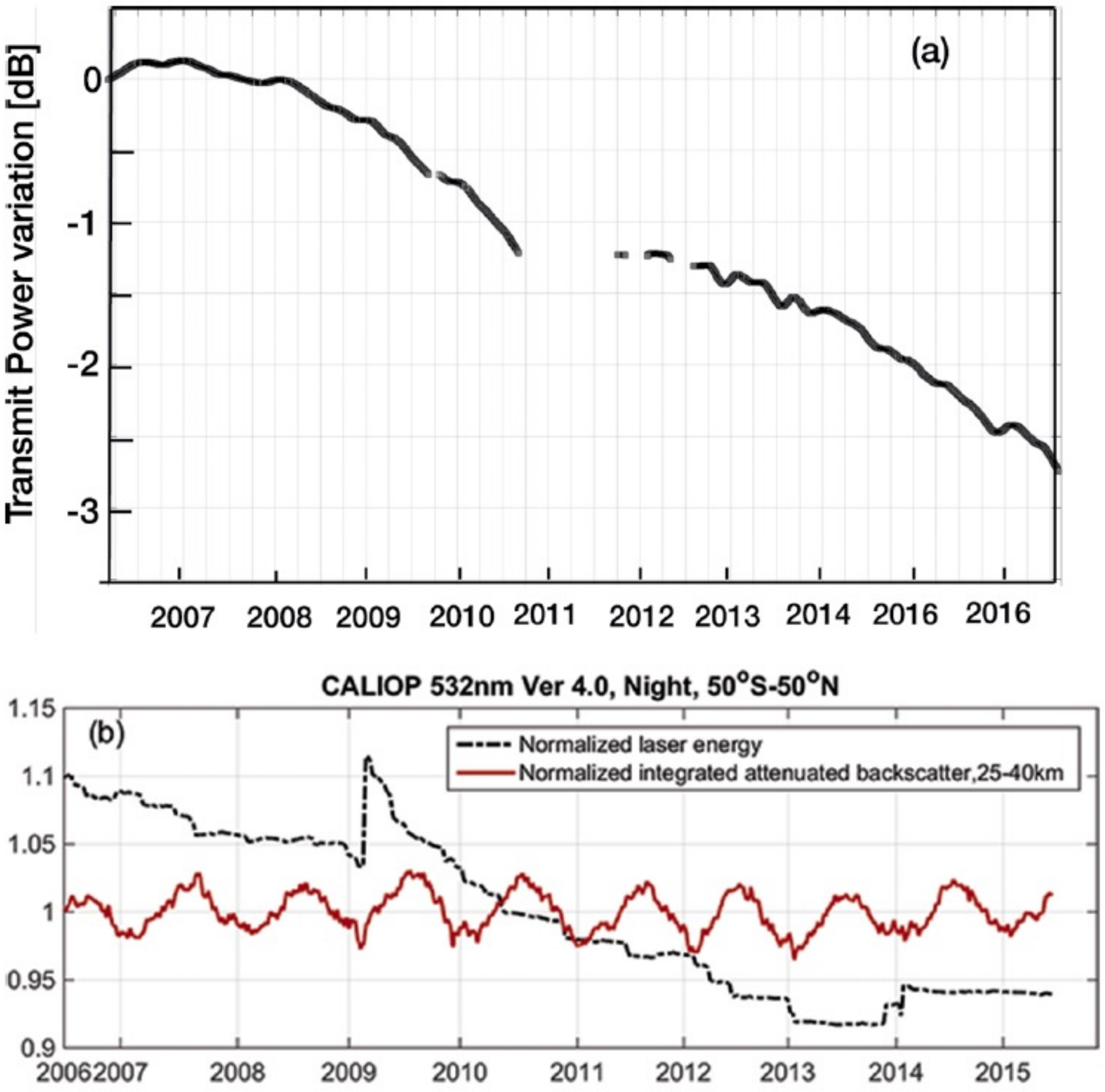
Background

- CALIPSO CALIOP and CloudSat CPR active sensors can detect cloud vertical structures, which is an advantage compared to passive sensors such as MODIS.
- However, the cloud trend study using active sensors 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 are compared with those from MODIS?

Potential Issues in CALIPSO and CloudSat Sensor Degradations (Stephens et al. 2018)



(Stephens et al. 2018)

- The CPR sensor output power degraded over time, causing changes in the 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 the signal-to-noise ratio might have changed over time.

Cloud Selection Method in CALIPSO and CloudSat Measurements

Clouds are selected to minimize impacts of sensor degradation and for more comparable comparison to MODIS cloud measurements:

- **CloudSat Clouds**
  - Clouds with radar reflectivity (Z) ≥ –25 dBZ

    Clouds with Z < -25 dBZ are excluded since these clouds could be detected in earlier mission due to the change in minimum detectable radar reflectivity .

- **CALIPSO clouds**
  - Horizontal averaging scale for cloud detections (HOR) ≤ 20 km

    CALIPSO clouds are detected either from a single beam (1/3 km) or spatial averaging of several beams (1, 5, 20, or 80 km). The 80-km clouds are excluded since these are mostly appeared over the Arctic and a strong decreasing trend is noted.
  - CAD (cloud-aerosol-discrimination) score ≥ 20

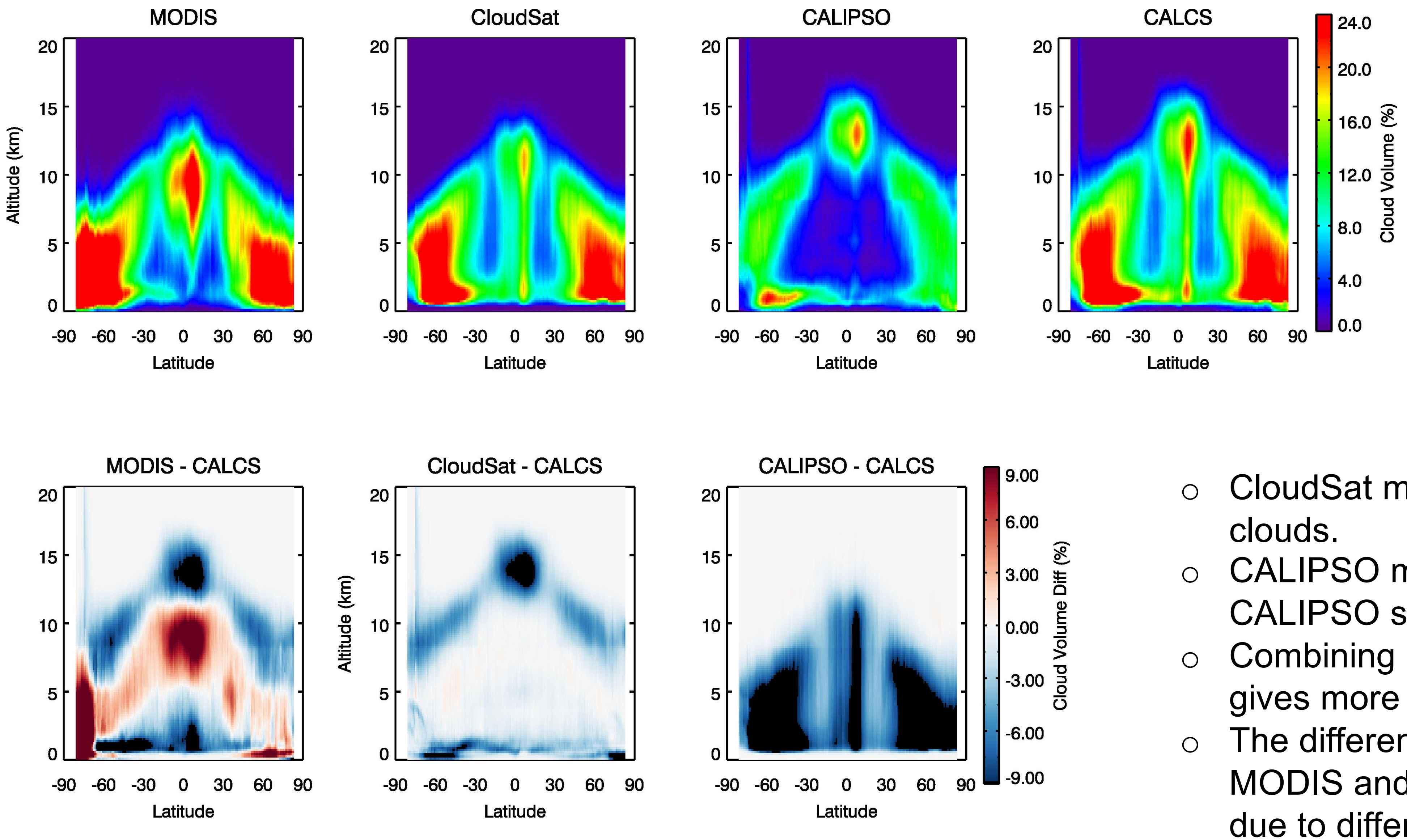
    The CAD score represents a confidence level of the detected clouds. When CAD = 0, there is no confidence and there is a higher chance of aerosol contamination. Since the clouds with CAD=0 appears near surface, these clouds are excluded.
  - Cloud optical depth (τ) ≥ 0.3

    MODIS misses clouds with $\tau < 0.3$ (Kato et al. 2019). Therefore, for more consistent comparison, clouds with $\tau < 0.3$ are also excluded in CALIPSO measurements. Also those thin clouds are more affected by the sensor degradation issues.

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

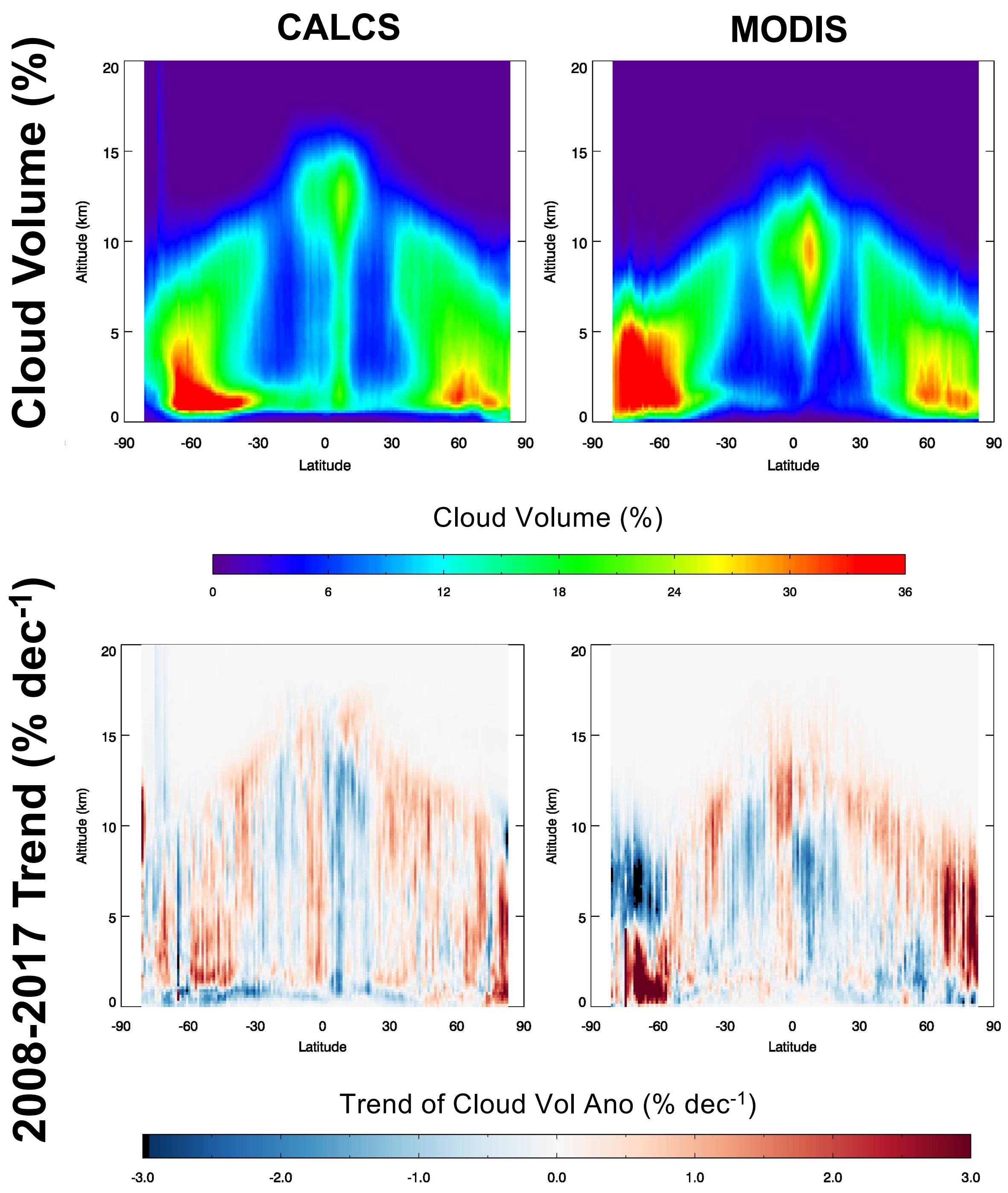
2008, Daytime

(Z ≥ –25 dBZ) (CAD≥20, HOR≤20km, τ≥0.3)



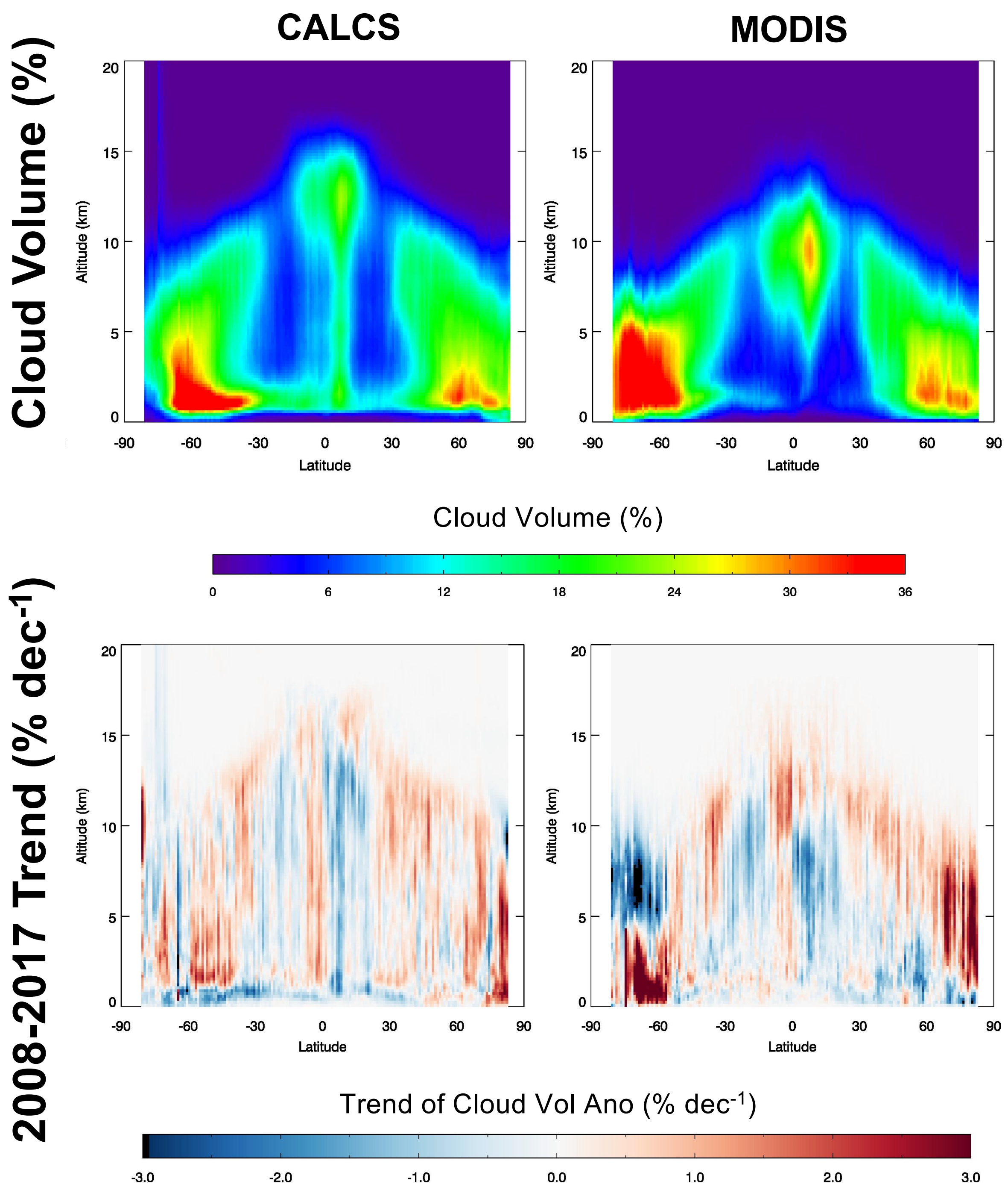
- CloudSat misses thin cirrus and low clouds.
- CALIPSO misses mid/low clouds when the CALIPSO signal is fully attenuated.
- Combining CALIPSO+CloudSat (CALCS) gives more complete picture of clouds.
- The differences in cloud amounts from MODIS and CALCS seem to be mostly due to different cloud heights.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

CALIPSO+CloudSat (CALCS) versus MODIS

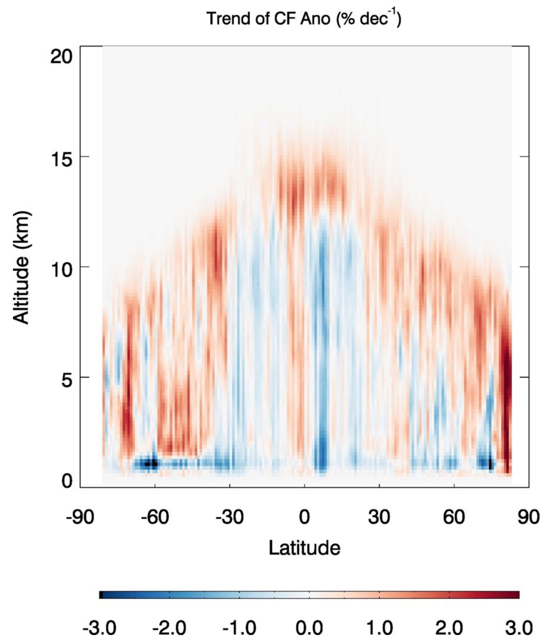


- Both CALCS and MODIS indicate an increase of uppermost clouds and a decrease underlying clouds over 60°S–60°N.
- Cloud altitudes in CACS and MODIS trends over the Antarctic are different: Probably due to uncertainties in MODIS cloud height retrievals in temperature inversion or skin temperature issues.

CALIPSO+CloudSat (CALCS) versus MODIS

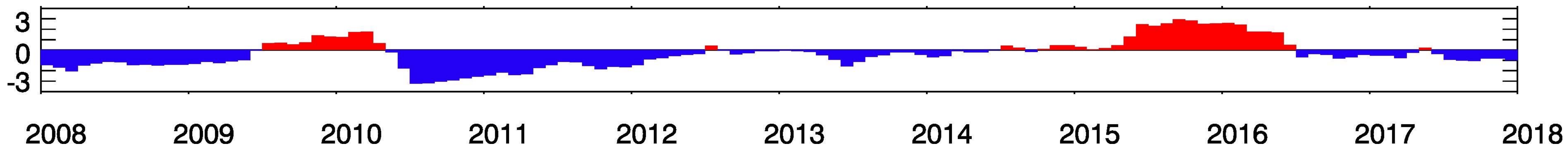


2008-2017 Trend
from CloudSat



CloudSat trend is also comparable to MODIS or CALCS trends. However, it should be noted that a significant amounts of low clouds (< 1 km) are missed by CloudSat.

ENSO Index for 2008–2017

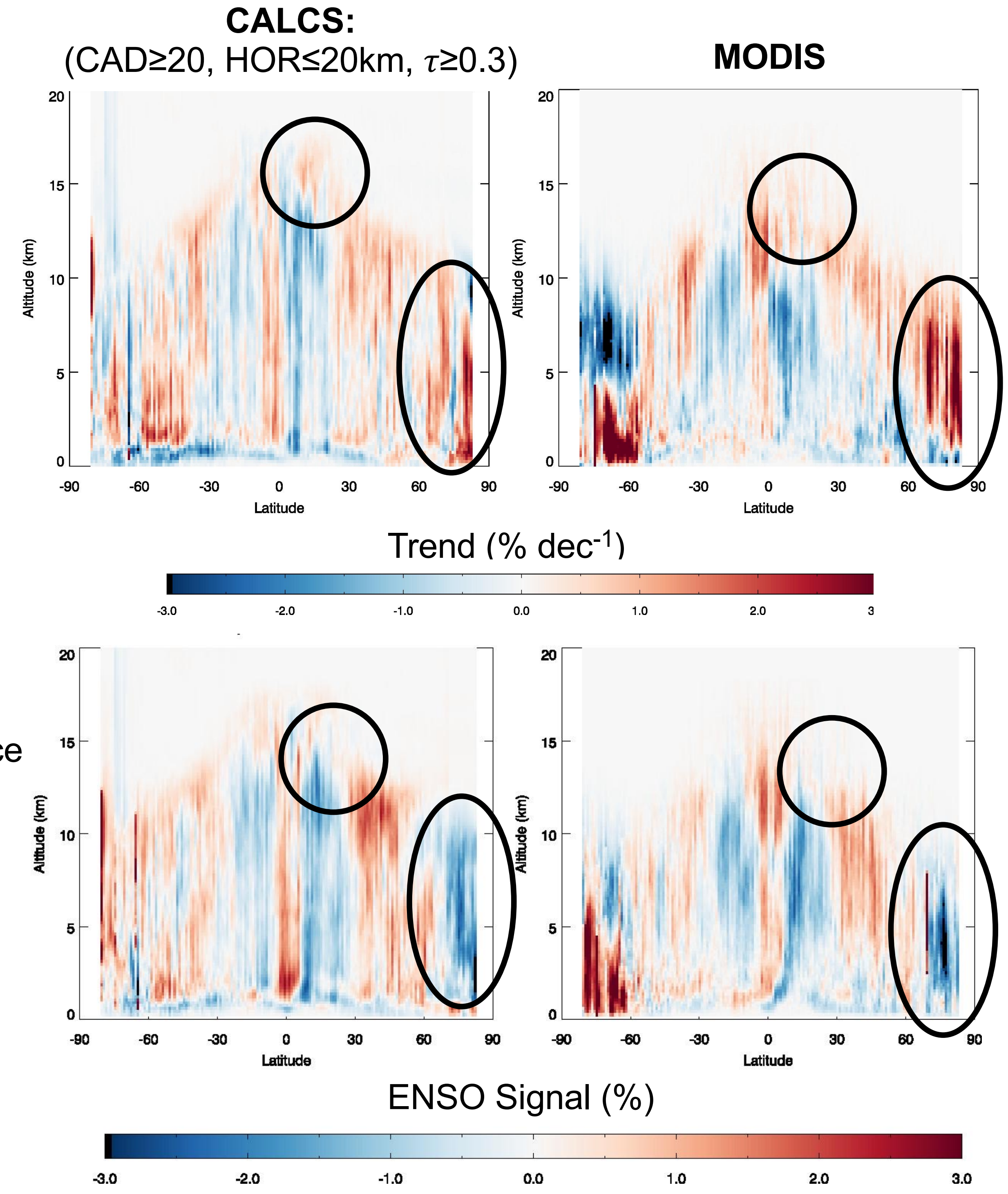


- Note that strong La Niña events occurred in the earlier time of the A-train mission, and strong El Niño events during A-train mission.
- As a result, the cloud trend over this period might be related to ENSO signals (La Niña to El Niño phase transition).

Cloud Trends versus ENSO Signal

2008-2017
Cloud Trend
(% dec^{-1})

ENSO Signal:
Cloud volume difference between El Niño (MEI ≥ +0.5) and La Niña (MEI ≤ –0.5) Periods

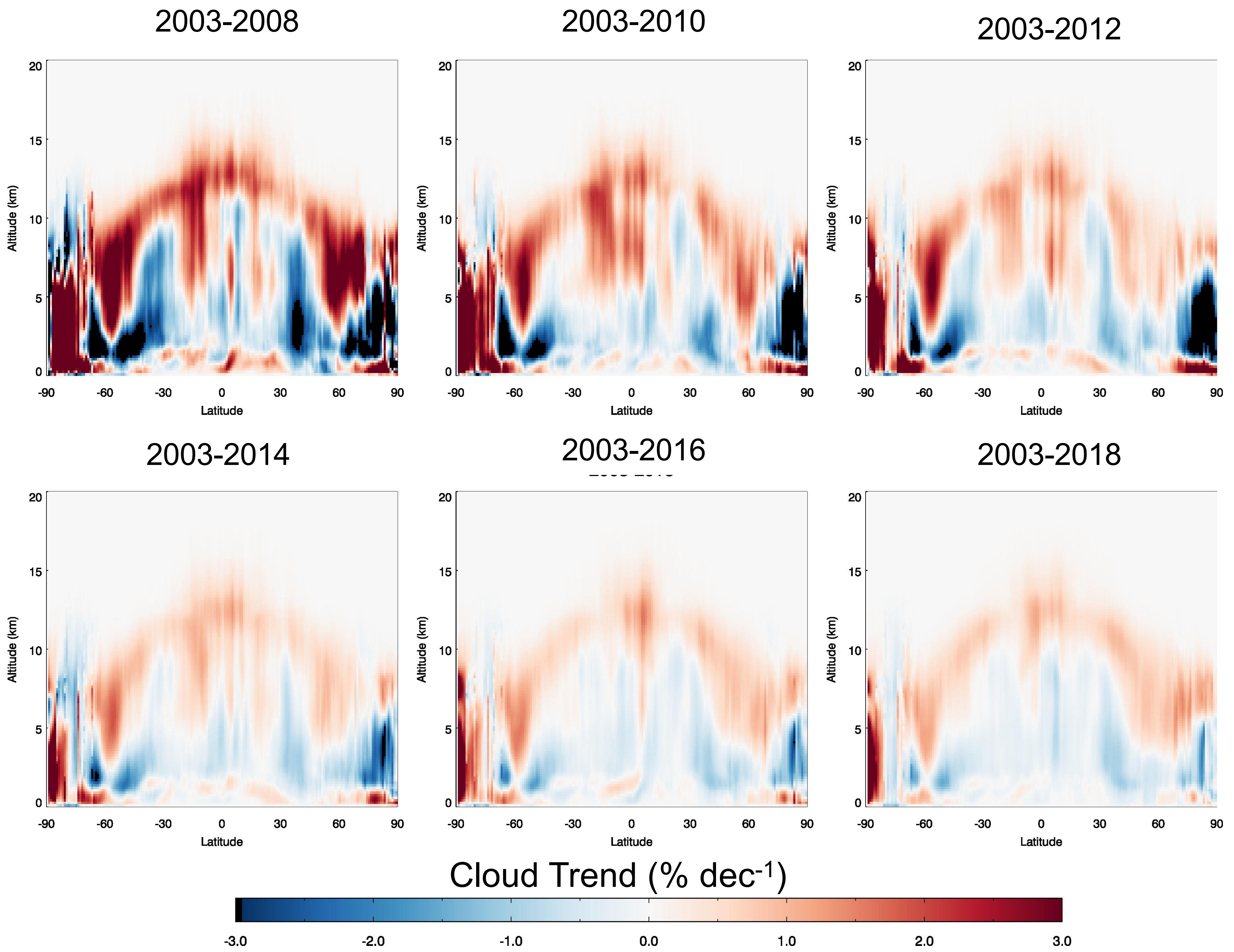


- Over the Arctic, ENSO signal is negative, while the trend is positive.
- While the positive cloud trend is noted in uppermost cloud layers in most of regions between 60°S–60°N, ENSO signal dose not show this feature for all latitude regions. This might indicate other factors caused increasing uppermost cloud layers. One possible explanation is "rising high clouds", or "upward shift of high clouds, suggested by theory, climate modeling, and satellite observations (Wetherald and Manabe 1988; Zelinka and Hartmann 2010; Voigt et al. 2019; Aerenson et al. 2022; Richardson et al. 2022).

Cloud Trends For Various Periods Using MODIS Aqua

Aqua MODIS, all sampling

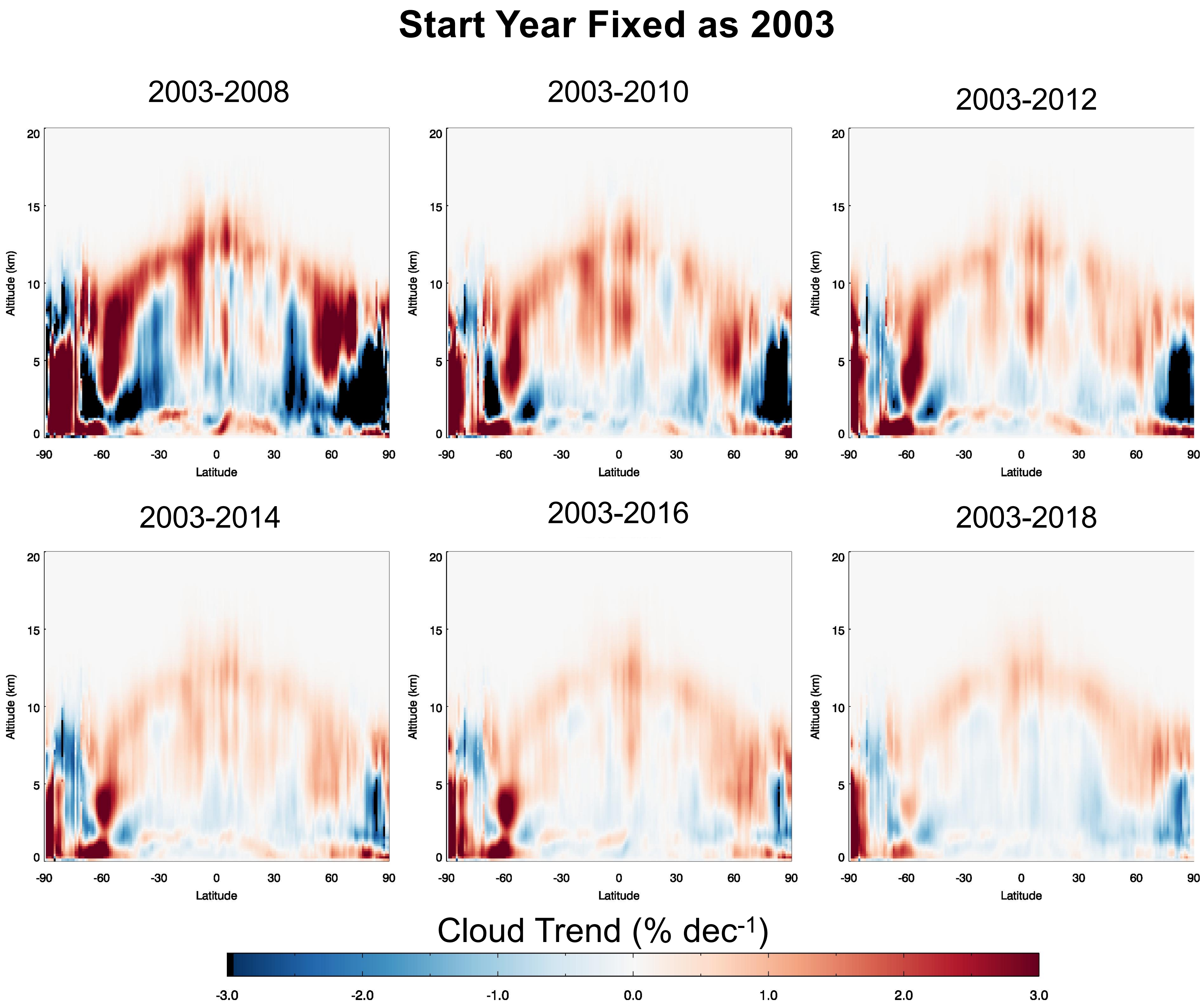
Start Year Fixed as 2003



- The 10-year period (2008-2017) might not be long enough to capture the rising high cloud features (Takahashi et al., 2019; Davies et al. 2017; Chepfer et al. 2018). Therefore, a longer period is considered using MODIS observations.
- An increase of uppermost cloud layer is more evident when the period of MODIS observation is extended.
- All periods show increasing trends of uppermost high clouds for most latitude regions.

Zonal Cloud Trends For Various Periods Using MODIS Terra

Terra MODIS, all sampling

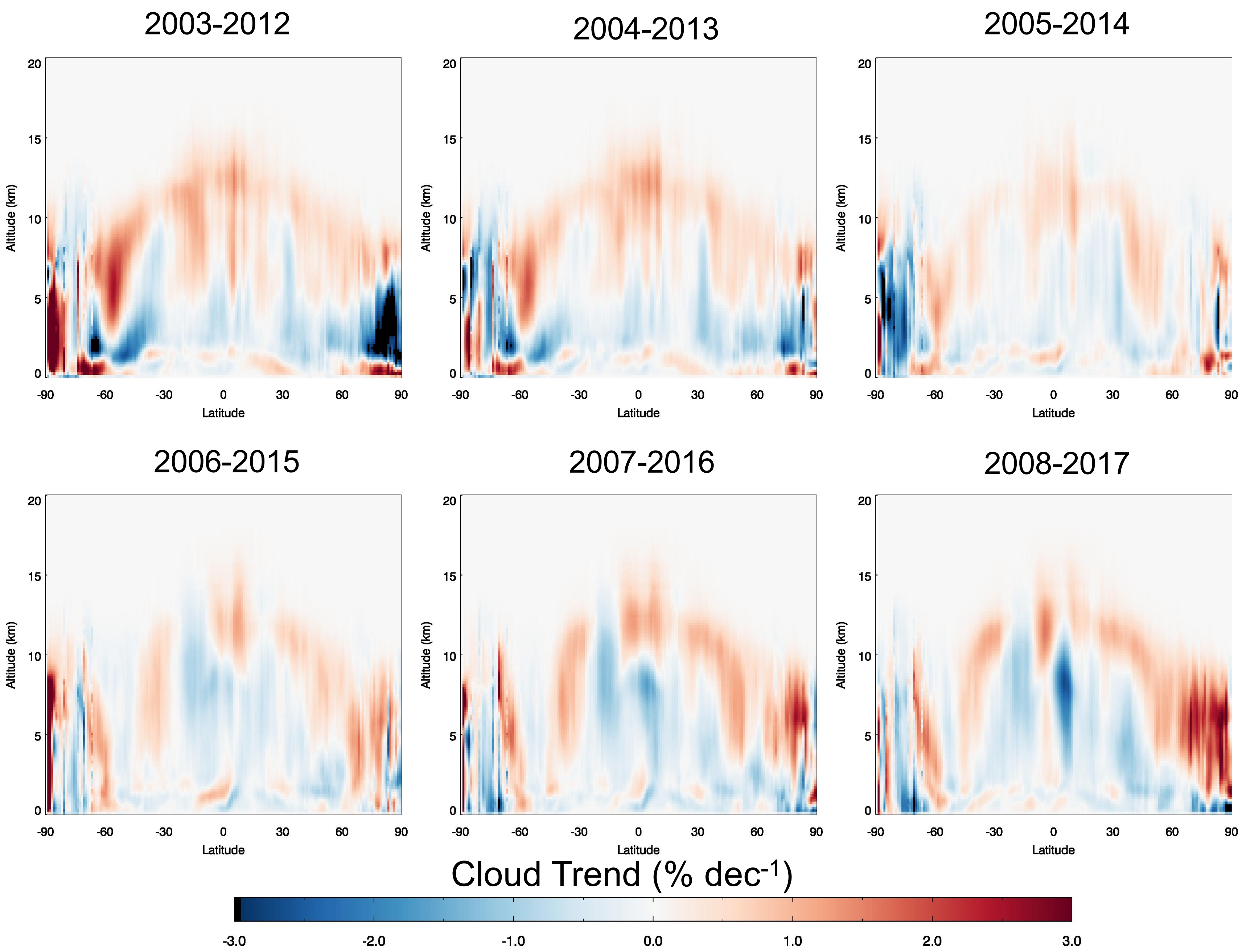


- Cloud trends from Terra Aqua is also very similar results to those from Aqua MODIS.

Zonal Cloud Trends For Various Periods Using MODIS Aqua

Aqua MODIS, all sampling

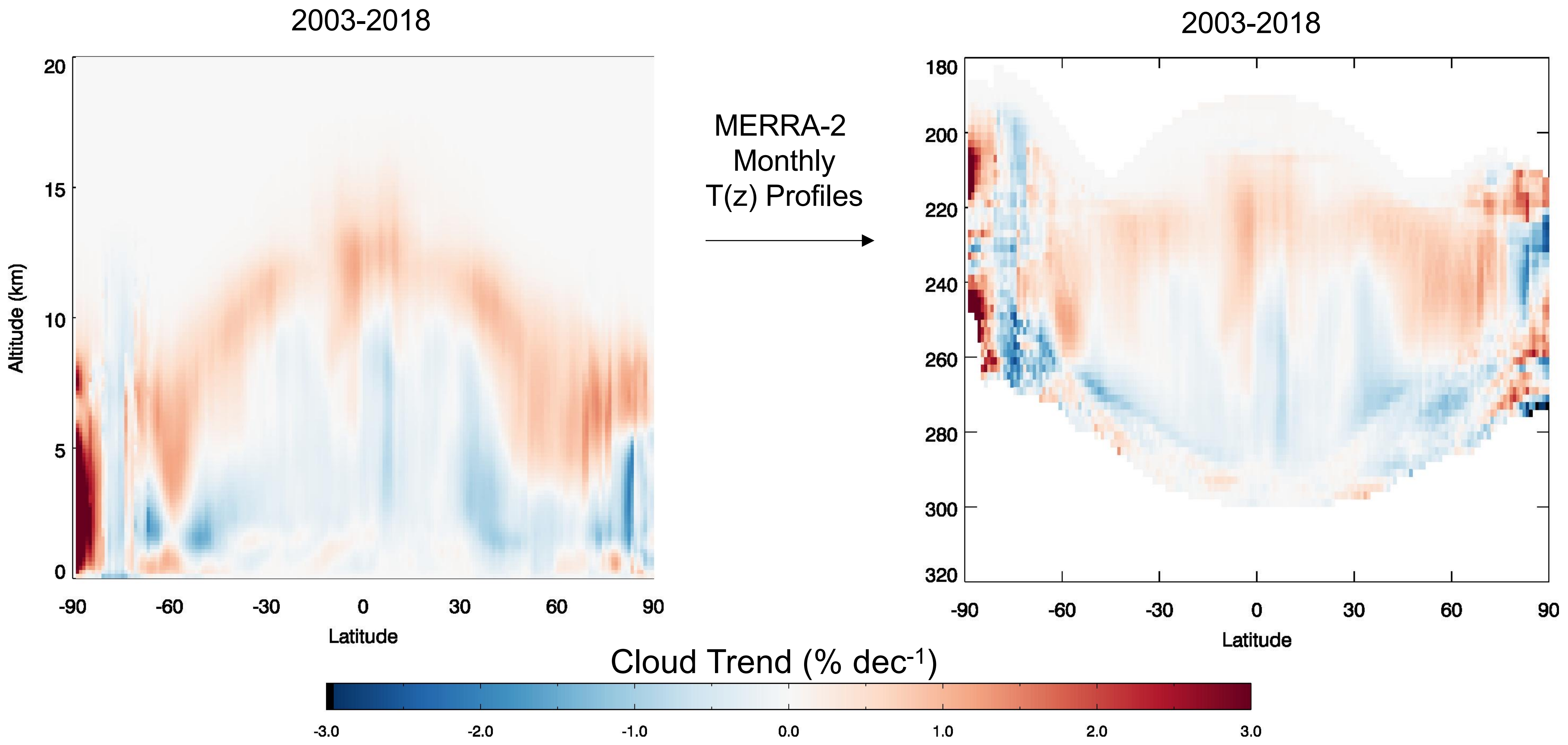
Length of Periods Fixed as 10 Years



- The rising high cloud feature is little weaker in the later period, when we fix the length of the period as 10 years.

Aqua MODIS, all sampling

Would A Higher Cloud Bring A Cold Cloud Thermal Emission? Transform A Vertical Axis from Altitude to Temperature Using Reanalysis Temperature Profiles

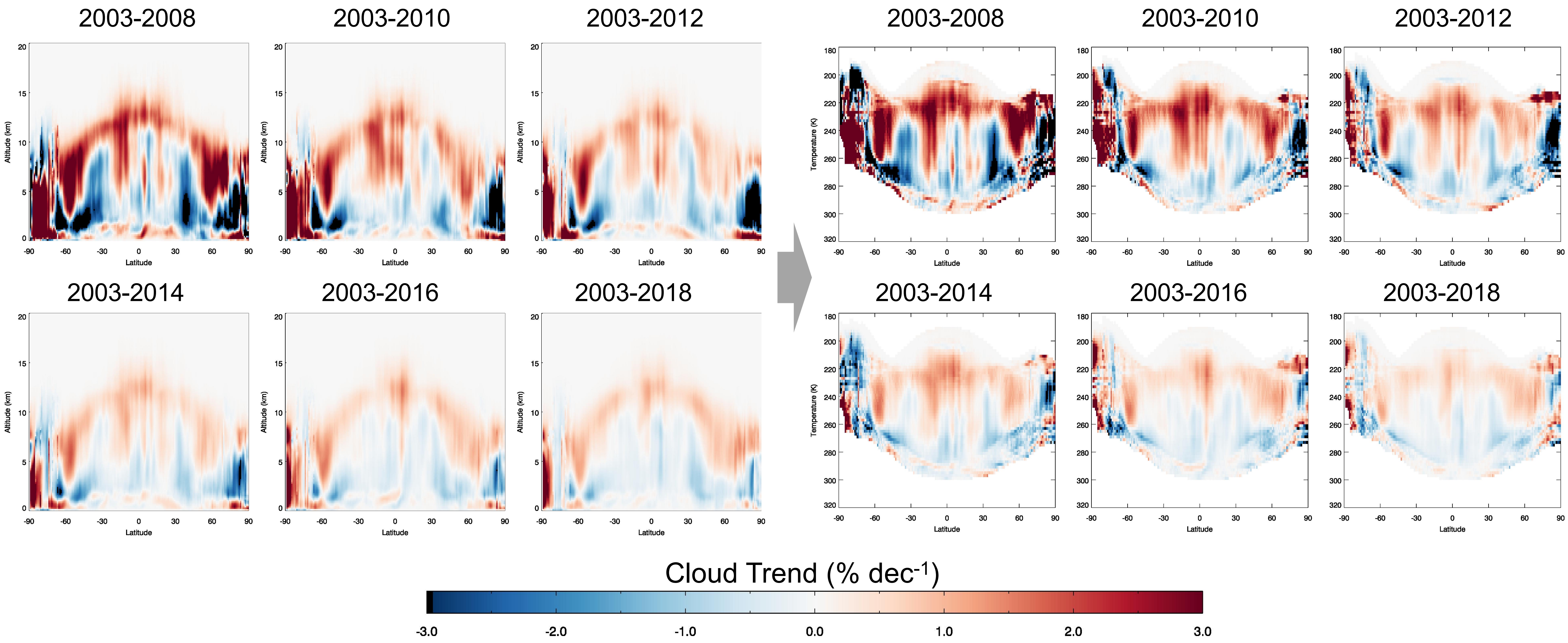


- As the cloud top heights of uppermost cloud layers increased, cloud occurrences at colder temperature (220–240 K) increased as well. This implies a colder cloud emission, and a positive cloud feedback.
- Near surface, cloud amount in warmer temperatures did not change.

Would A Higher Cloud Bring A Cold Cloud Thermal Emission?

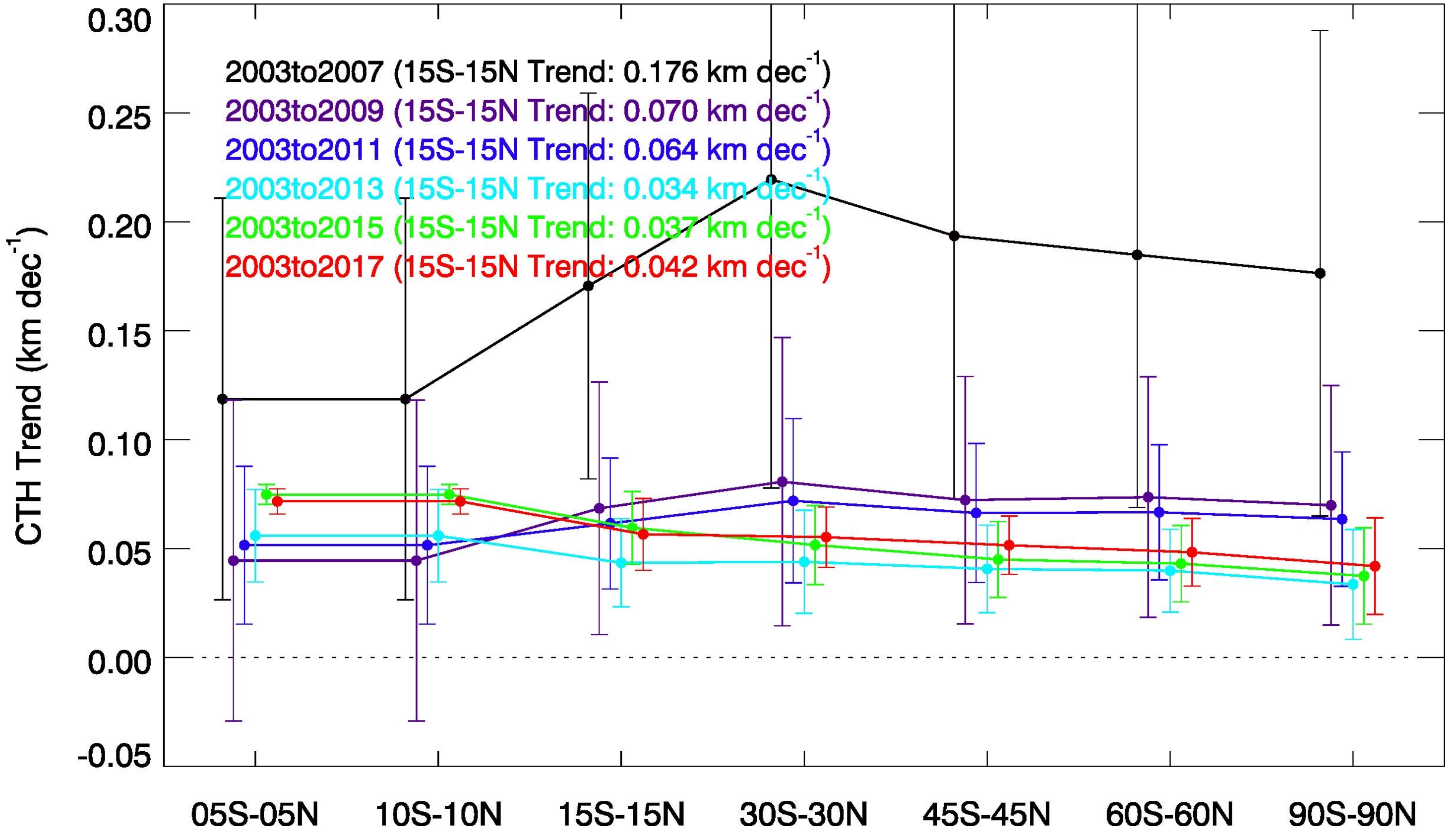
Aqua MODIS, all sampling

Start Year Fixed as 2003

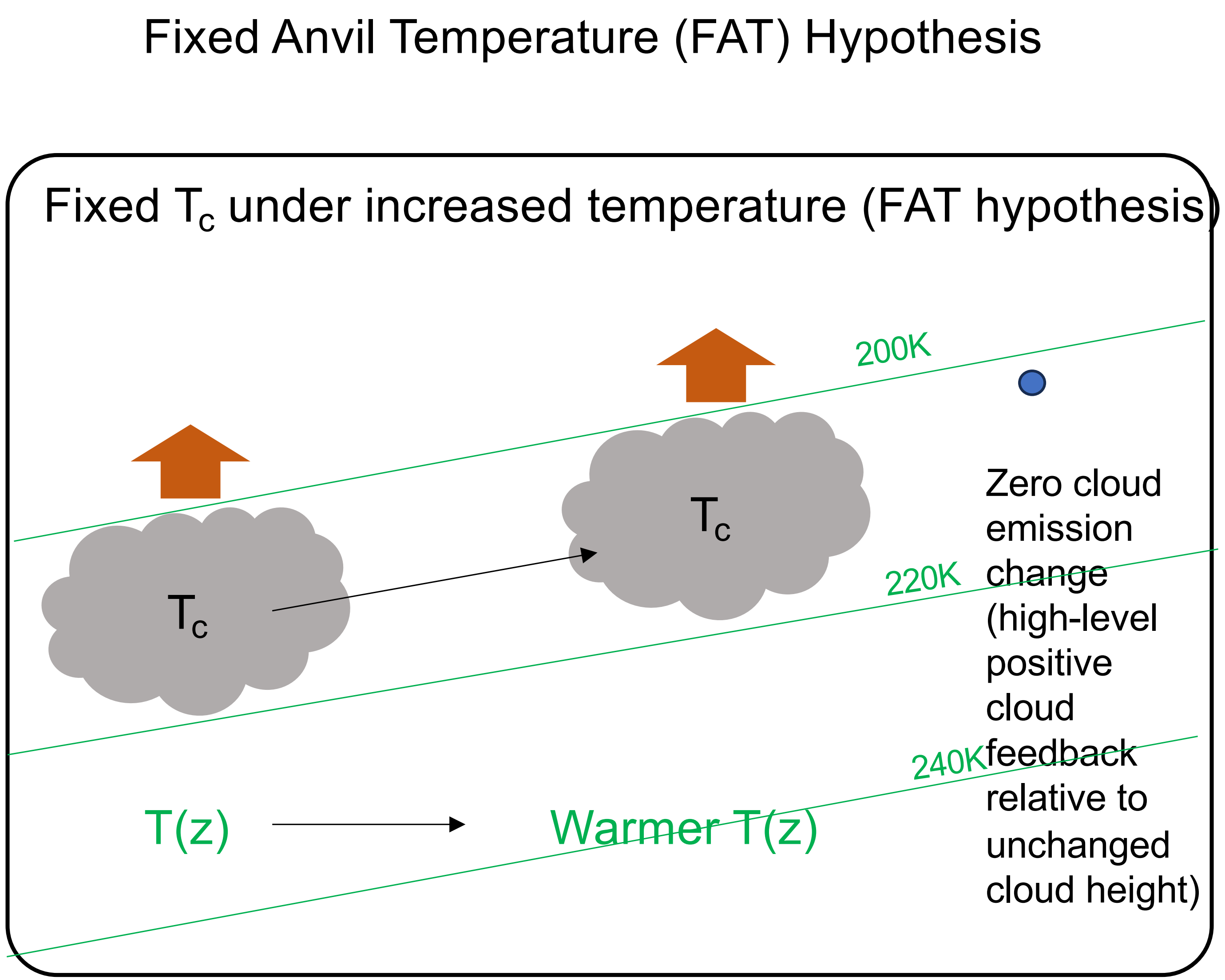


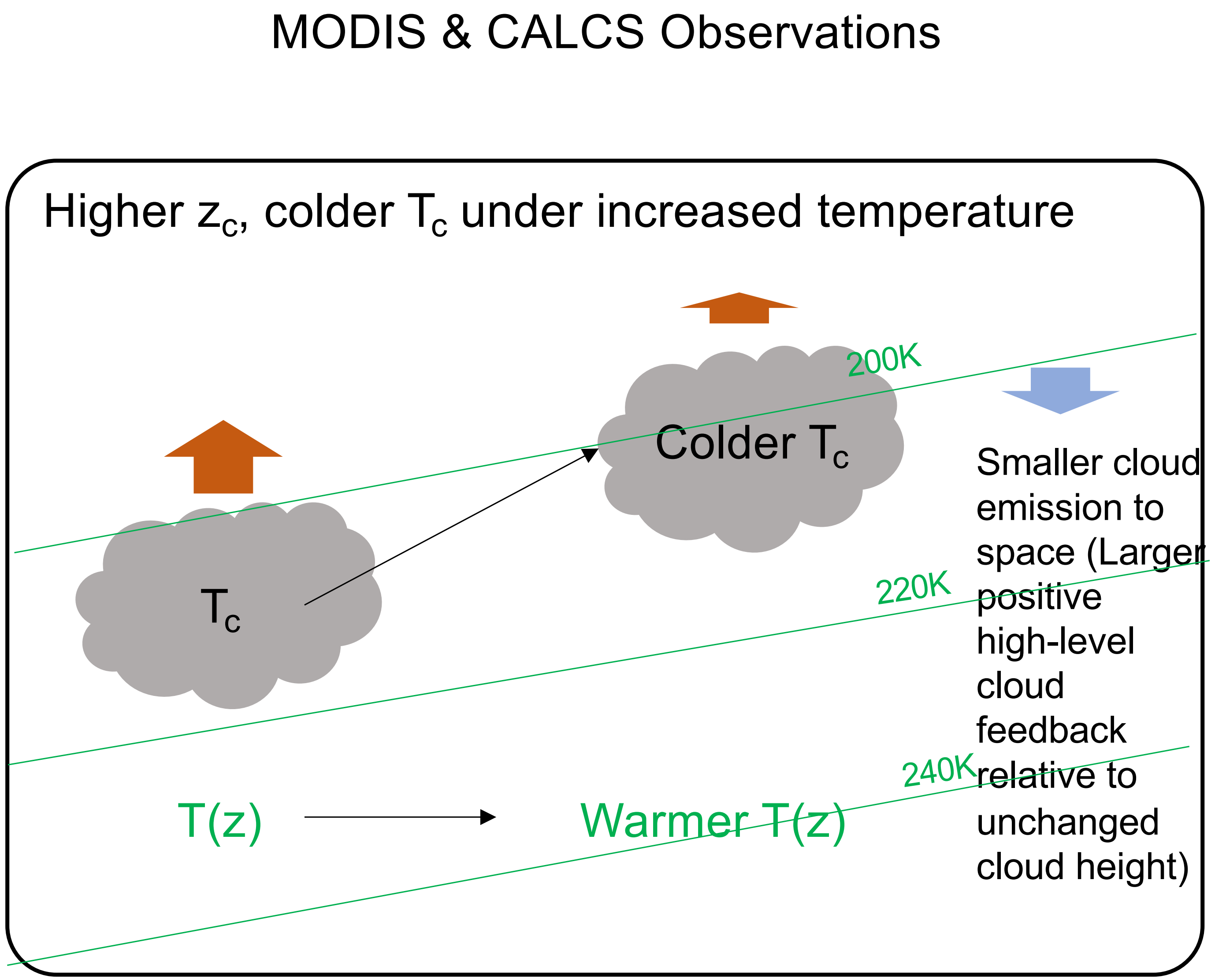
- As the cloud top heights of uppermost cloud layers increased, cloud occurrences at colder temperature (220 K) increased as well. This implies a colder cloud emission, and positive cloud feedback, given that the cloud emissivity remain similar.

Trends of High-Level Cloud Top Boundary (Top 10-18 km) (Aqua MODIS)



- Earlier studies suggested comparable magnitudes of cloud top height increase (~ 60 m dec-1; Richardson et al. 2022).
- Temperature trend is 0.22 K dec^{-1}. To conserve cloud top temperature, with assuming a rough lapse rate of 6K km^{-1}, it would be 0.036 km dec^{-1}. Therefore, clouds rise more than the rise of isothermal lines.





- Changes in cloud optical depth or emissivity also affects OLR changes with rising high clouds, requiring further examination.
- A colder cloud temperature is also recognized in other studies using satellite measurements (Liu et al. 2023)
- The positive high cloud feedback also interacts with water vapor and surface temperature feedback.

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 HOR ≤ 20 km and CAD ≥ 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 a positive cloud feedback.

Thank you for your attention!

Please contact to seung-hee.ham@nasa.gov if you have any questions.