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Cloud Changes Observed from MODIS and CALIPSO-CloudSat (CALCS)

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Objectives

1. Understand differences in cloud detections from MODIS, CALIPSO, and CloudSat
2. Filter CloudSat clouds to reduce the impact of CPR sensor degradation and filter CALIPSO clouds for a more consistent comparison with MODIS
3. Combine CALIPSO and CloudSat (CALCS) for a better cloud detection
4. Compare 10-year cloud trends from MODIS and CALIPSO+CloudSat (CALCS)

Strength and Weaknesses of MODIS, CALIPSO, and CloudSat

	MODIS	CALIPSO	CloudSat
Strength	• Cloud column optical depths are directly retrieved from the visible channel radiances (radiatively well constrained). • Broader spatial coverages from cross-track scans	• Cloud profiles with a high resolution (30 or 60 m).	• CloudSat can see through most of the deep convective clouds • Detailed vertical cloud structure with a 480 m resolution with oversampling every 240 m.
Weaknesses	• Detailed vertical structures can be missed. • Large uncertainties for multi-layered clouds and clouds over snow/ice	CALIPSO signal is fully attenuated for the optical depth > 5 or so. ➜ Most of the cloud tops are detected, but not the cloud lower parts.	• Thin cloud layers (< 120 m) can be missed. • Low clouds (< 1 km altitude) can be missed due to surface clutter. ➜ 2/3 of total clouds are only detected (total MODIS/CALIPSO cloud fraction is ~ 65%, while CloudSat total cloud fraction is around 40%).

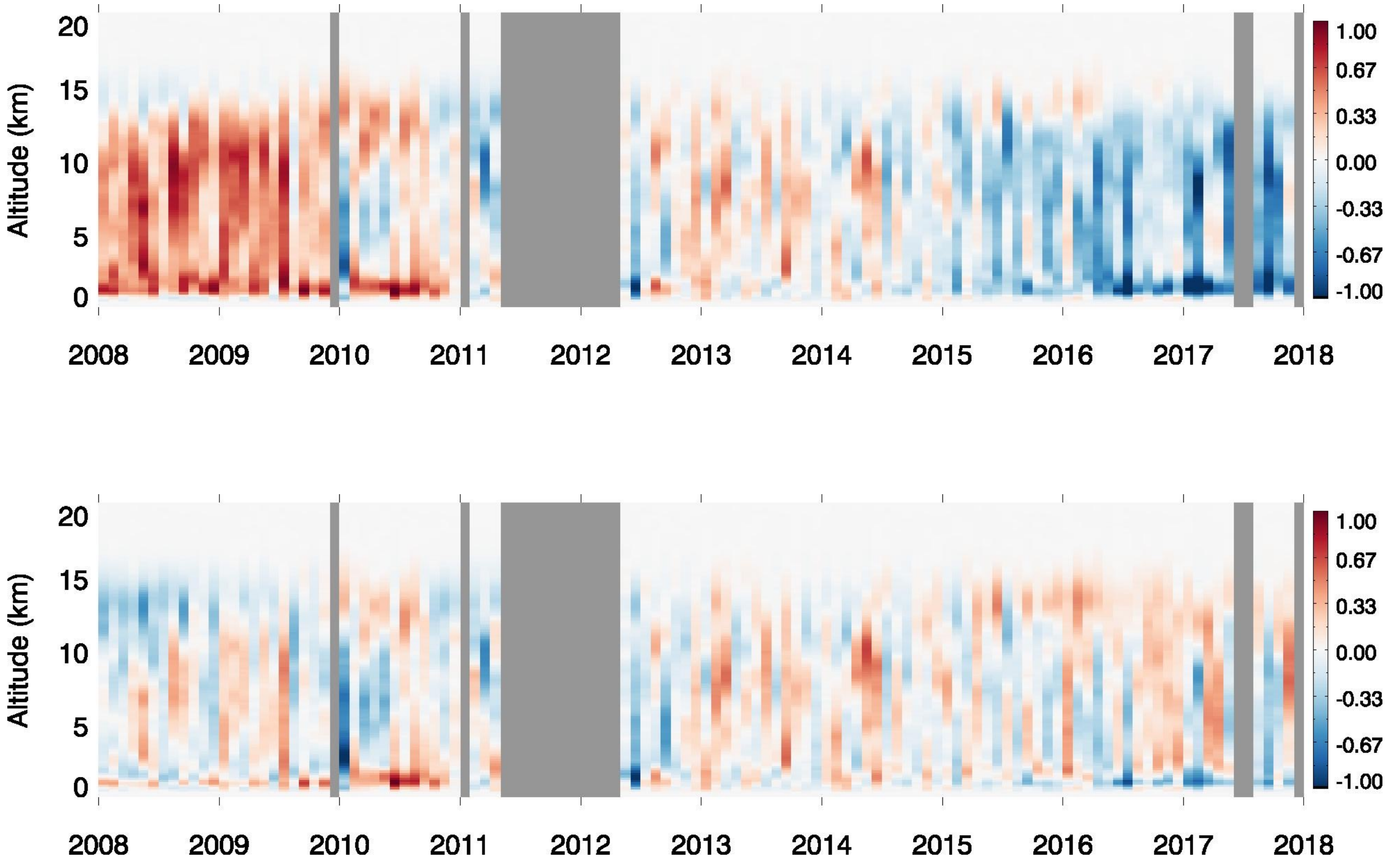
Filtering CloudSat Clouds to Reduce Impacts of Cloud Profiling Radar (CPR) Degradation

- CloudSat CPR minimum detectable radar reflectivity has increased over time, meaning that the background noise has increased over time. As a result, the clouds with small reflectivity (mostly from small cloud particles) is getting missed more over time.
- To prevent the cloud trend artifact related to the CloudSat minimum signal change, the CloudSat team (Matthew Lebsock) suggested using a threshold of Z_{dB} ≥–25 dBZ for clouds.

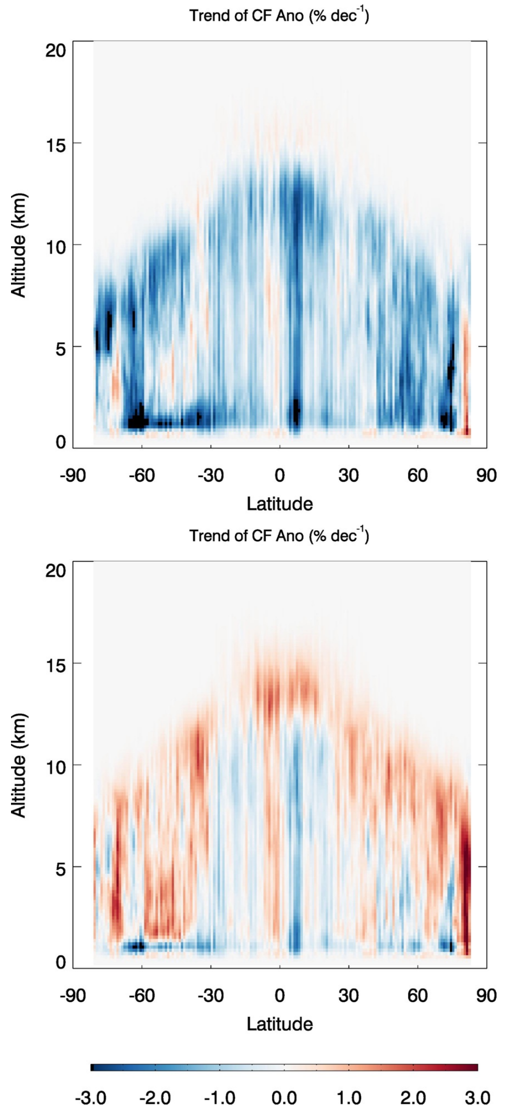
60°S-60°N CloudSat Cloud Occurrence Anomaly (%)

Without a Threshold of Radar Reflectivity (Z_{dB})

CloudSat Clouds with Z_{dB} ≥–25 dBZ



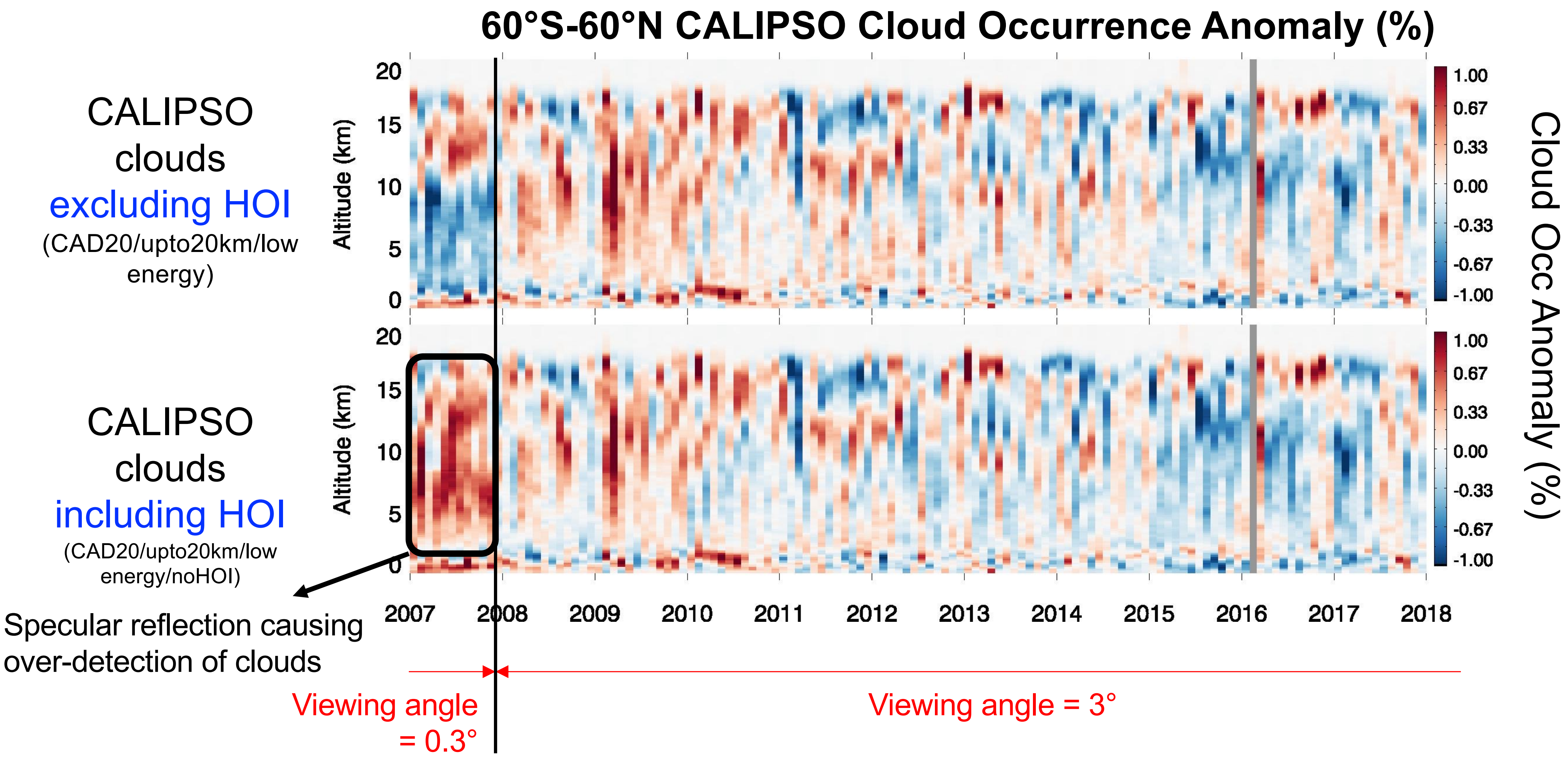
2008-2017 CloudSat Cloud Trend (% dec^{-1})



The threshold of Z_{dB} ≥–25 dBZ seems to successfully remove the artifacts related to CPR degradation.

Large CALIPSO Anomaly in 2007 Related to the CALIPSO Viewing Angle Changes

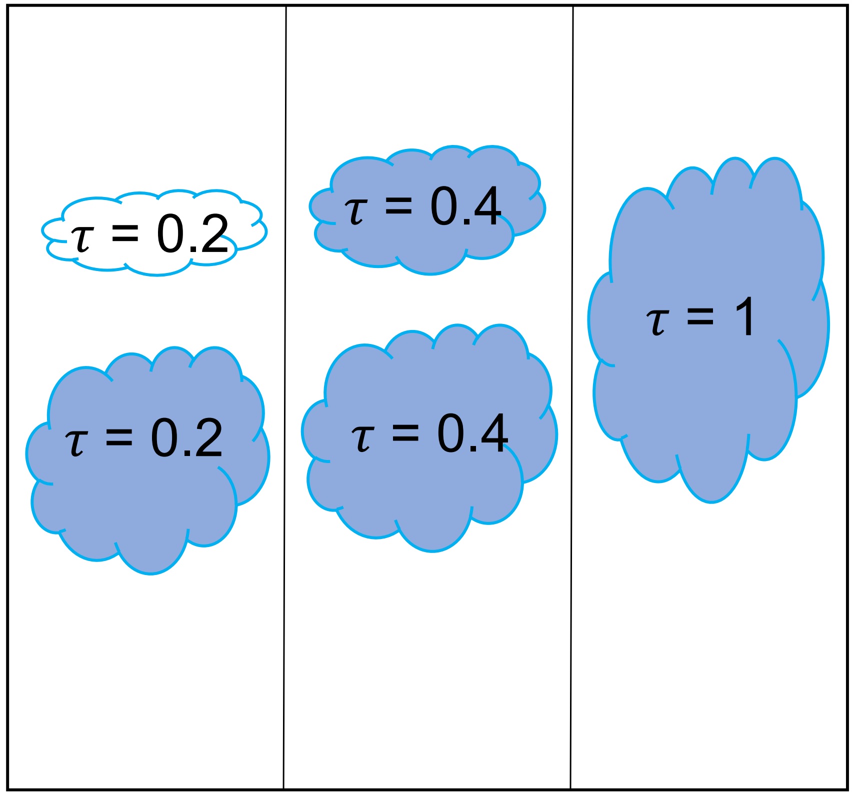
The small viewing angle (0.3°) prior to November 2007 caused over detection of horizontally oriented ice (HOI) layers due to the specular reflection from hexagonal smooth crystal faces that are oriented perpendicularly to the incident lidar beam (Avery et al. 2020).



- When CALIPSO and CloudSat clouds are combined, the impact of the CALIPSO viewing angle is relatively small, compared to CALIPSO-only clouds. For avoiding potential discontinuities, we exclude 2007 in the current analysis.

Filtering Thin CALIPSO Clouds (τ < 0.3)

Examples of τ filtering



Two reasons for considering filtering CALIPSO thin clouds:

1. CALIPSO is sensitive to optically thin cirrus clouds (< 0.3), which is not detected by MODIS. Even if the changes in these layers are significant, the radiative impact would be relatively small compared to optically thicker clouds.

2. Optically thinner cloud detection is more influenced by the CALIPSO lidar background noise and sensor degradation. By removing the optically thin clouds, the potential impact of the sensor changes can be reduced in the cloud analysis.

The threshold of 0.3 is based on the previous study (Kato et al. 2018).

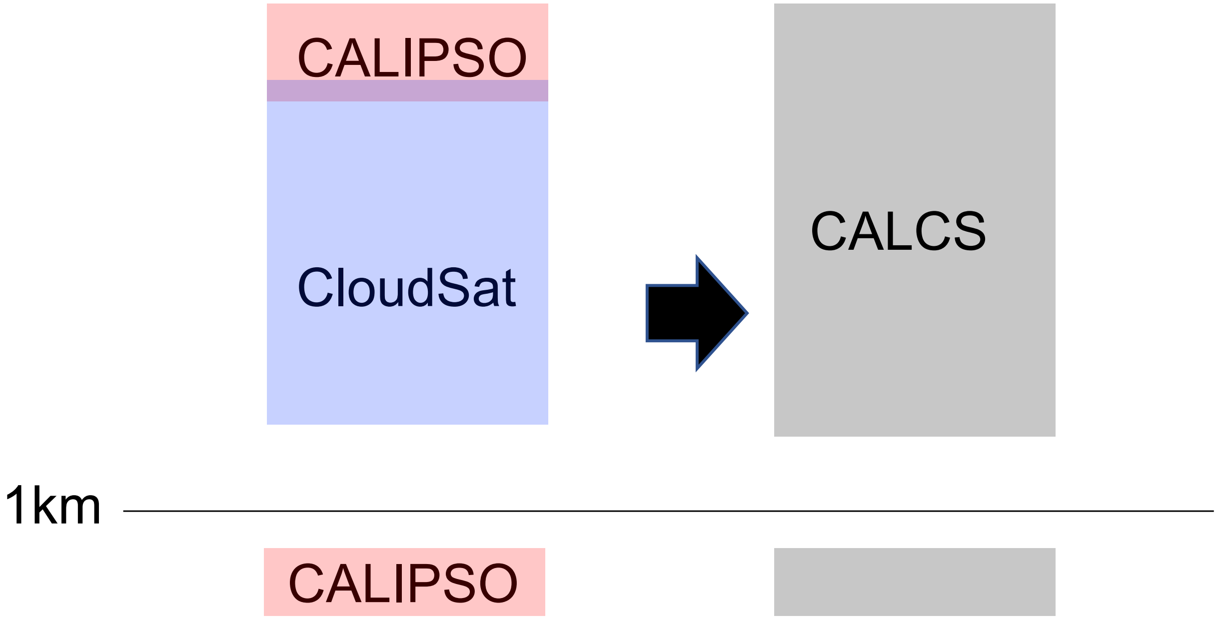
If the cloud optical depth integrated **from top** is smaller than 0.3, the layer is considered as clear (excluded from the cloud analysis). Note that the cumulative cloud optical depth from top is greater than 0.3, the layer is included even though the individual layer cloud optical depth is smaller than 0.3 (since MODIS will detect the cloud layer somewhere between the cloud layers).

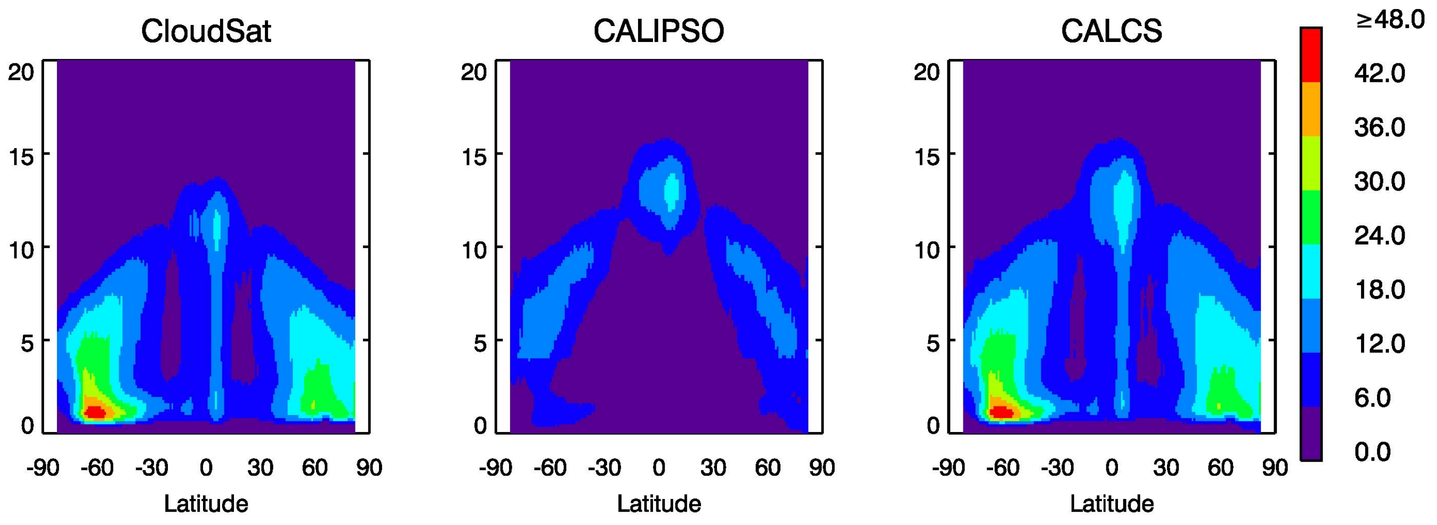
Combining CALIPSO and CloudSat (CALCS) Clouds

Benefits of combining two active sensors:

- CALIPSO nor CloudSat does not capture entire picture of clouds. CloudSat misses 2/3 of cloudy columns, mostly due to missing low clouds < 1 km. CALIPSO detects most of top parts of clouds, but cloud lower parts are often missed.
- When one sensor experiences degradation and the detection ability changes over time, another sensor can supplement the missing information (Ham et al. 2021).

There still exist limitation of very low clouds (< 1 km), underlying optically thick high/mid clouds.





Datasets (2008–2017, Daytime)

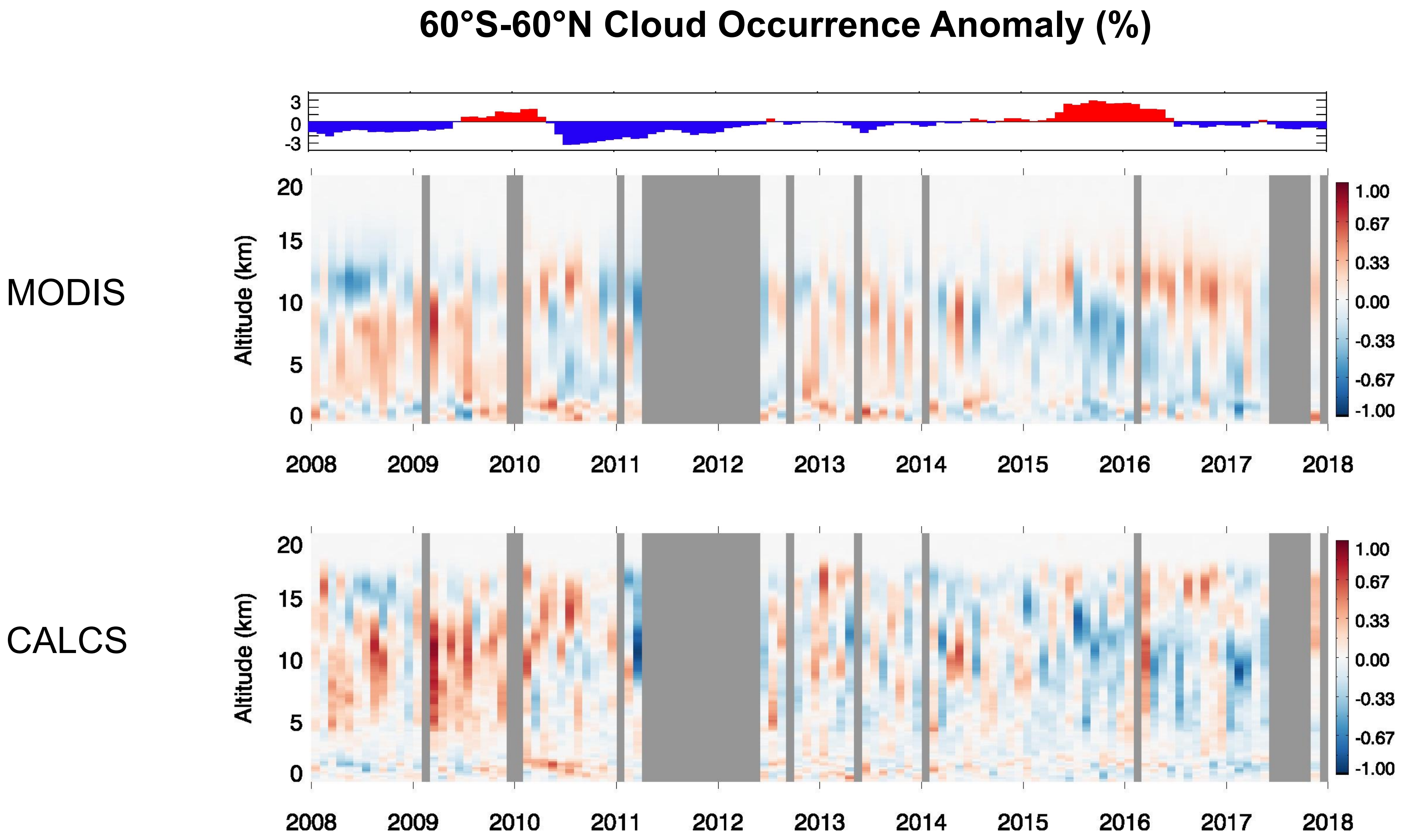
- **MODIS clouds**
  - ✓ Cloud mask is from CERES Ed4 SSF product.
  - ✓ Up to two MODIS cloud types per CERES footprint

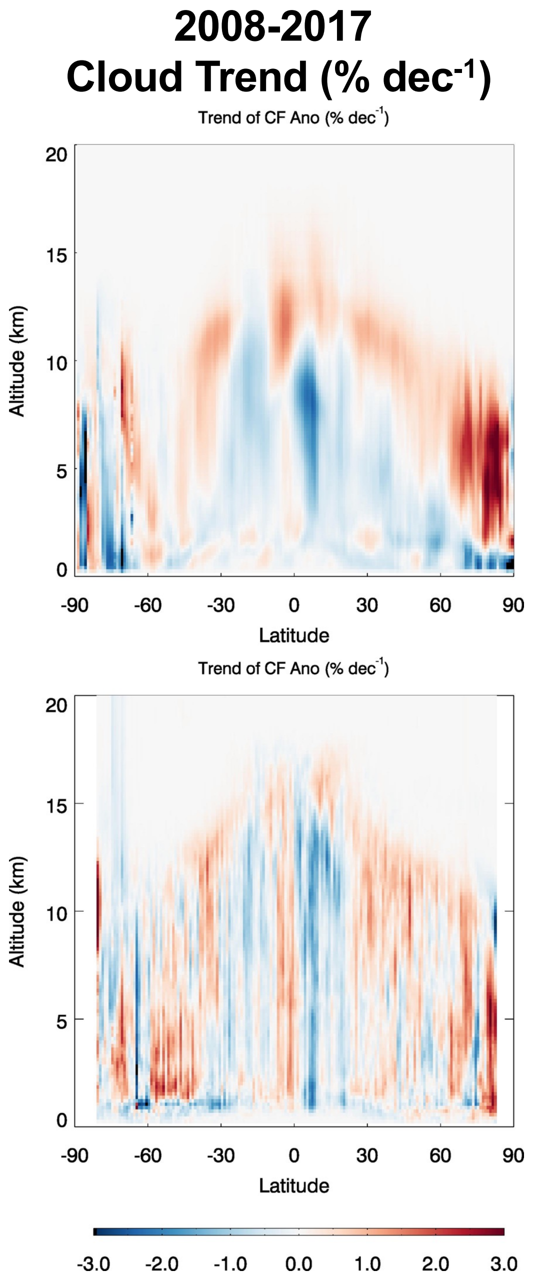
- **CALIPSO clouds**
  - ✓ Cloud mask is from CALIPSO V4 vertical feature mask (VFM) product
  - ✓ If the uppermost ice cloud layer has a cloud optical depth < 0.3, it is considered as clear.
  - ✓ Clouds detected from 1/3 (single lidar beam) or spatial averaging (1, 5, and 20 km) are included. For water clouds below 4 km, clouds detected from a single lidar beam are only included without spatial averaging. Clouds with CAD (confidence level) ≥ 20 are included.

- **CloudSat clouds**
  - ✓ Cloud mask is from CloudSat 2B-GEOPROF R05 product with a threshold value of 30 (cloud mask value ≥ 30; 0 = clear, 40 = cloudy).
  - ✓ Cloud layers with radar reflectivity < –25 dBZ are not considered as clear.

- **CALIPSO+CloudSat (CALCS) clouds**
  - ✓ Cloud layers from CALIPSO and CloudSat are merged. If at least one of the sensor detects clouds, these are included.

Comparison between MODIS and CALIPSO+CloudSat (CALCS) for Common Months



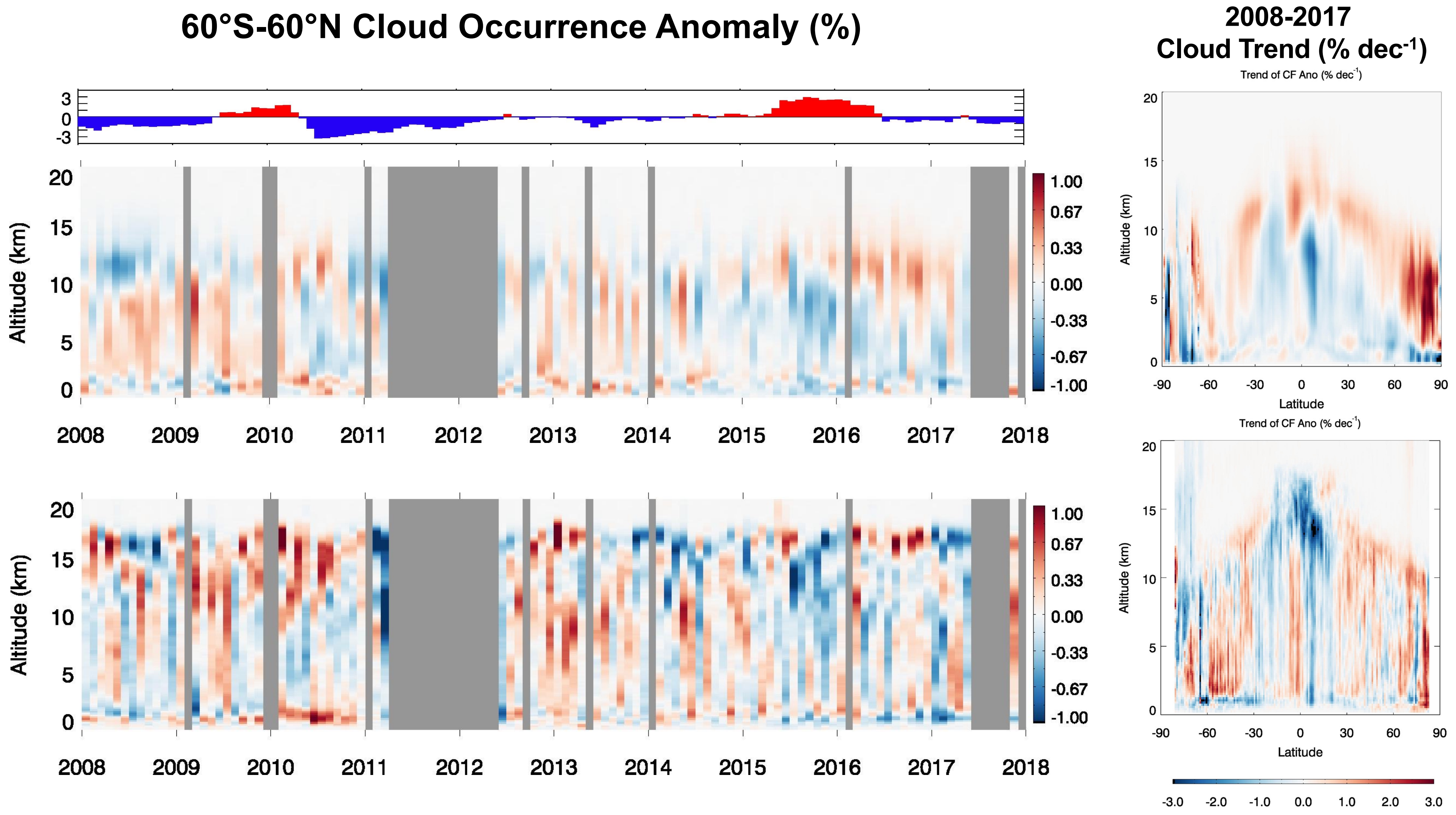


- A better sampling in MODIS from cross-track measurements (less noisy).
- Both MODIS and CALCS show an increase in the uppermost cloud layer and a decrease in underlying clouds for 30S-30N.
- Polar regions show different results due to 1) sparse sampling during daytime 2) large fluctuations of cloud anomalies 3) uncertainties in MODIS cloud detection over a bright surface 4) the impact of PSC in CALIPSO measurements.

If CALIPSO Tau Filtering was not applied..

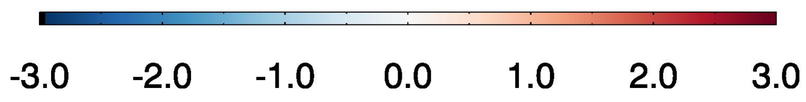
MODIS

CALCS
without
tau
filtering



- Without filtering CALIPSO clouds, high-cloud anomalies in CALCS are larger and more towards to negative, compared to MODIS cloud anomalies.

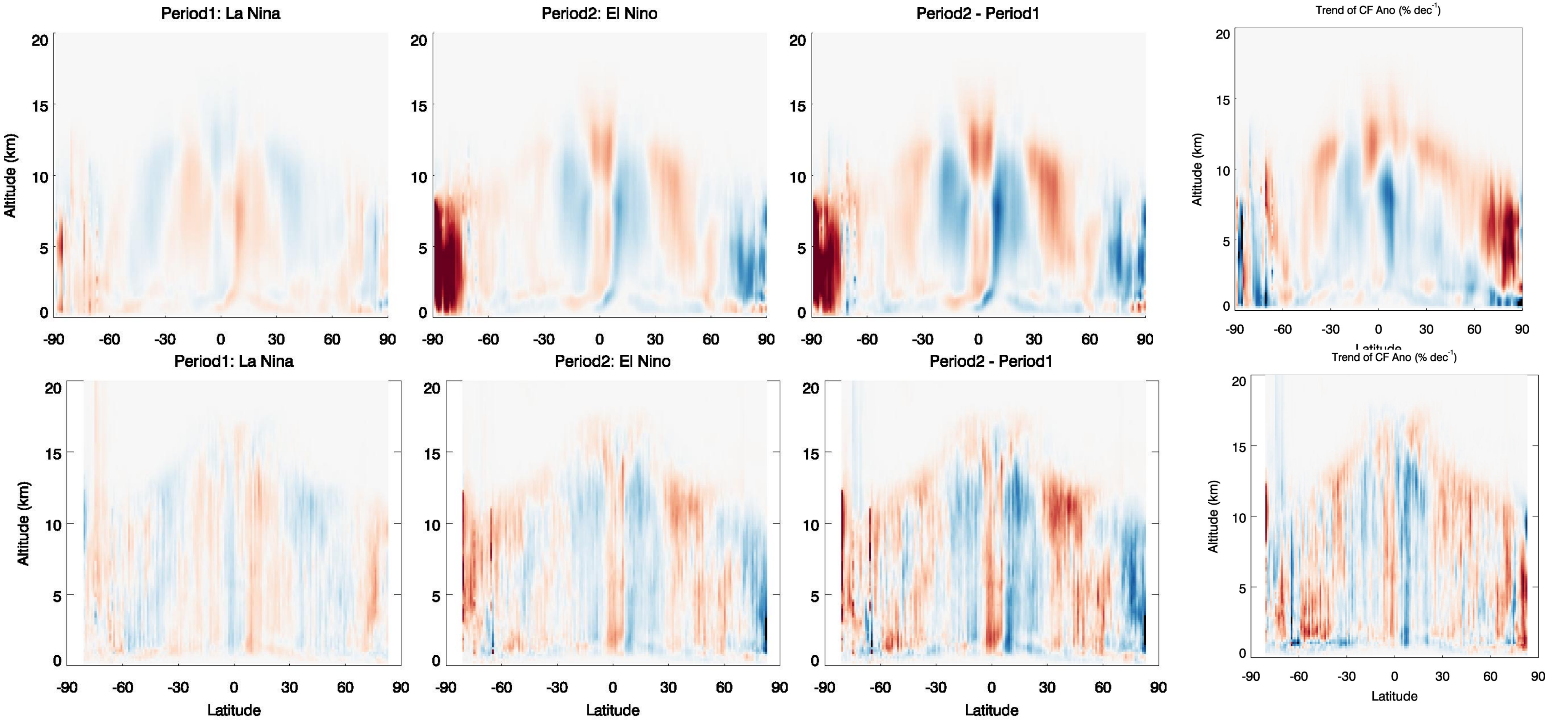
"ENSO Signals" versus "10-Year Cloud Trend"



	Cloud Anomaly (%) during La Niña (MEI ≤ –0.5)	**Cloud Anomaly (%) during El Niño** (MEI ≥ 0.5)	**ENSO Signal (%)** [El Niño]-[La Niña]	**2008-2017 Cloud Trend (% dec^{-1})**

MODIS

CALCS



- The 2008-2017 cloud trend is mostly driven by El Niño features. Besides the El Niño features, high clouds between 10°N to 30°N seem to increased over time.
- Large differences are shown over polar regions.

Where were the high-cloud top boundary increased?

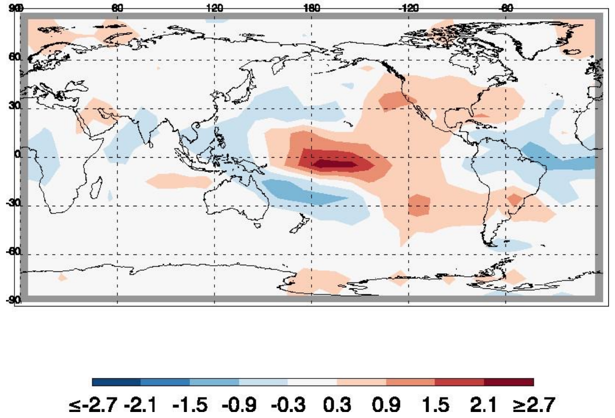
2008-2017 Trend (km dec^{-1})

CALCS cloud boundary of high clouds (top at 10-18 km) depending on ENSO phase

MODIS

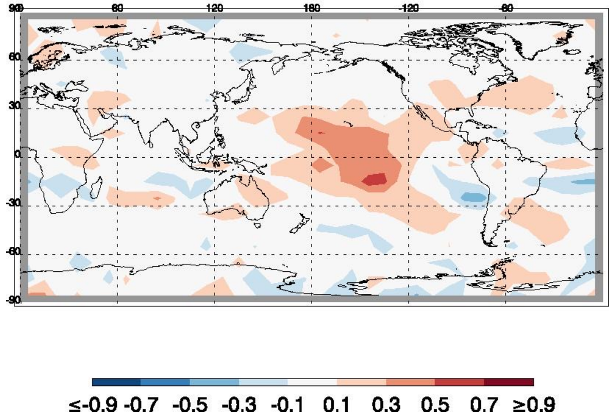
Cloud top boundary trend of all clouds

Trend (Glo Mean: 0.08±0.06 km/decade)



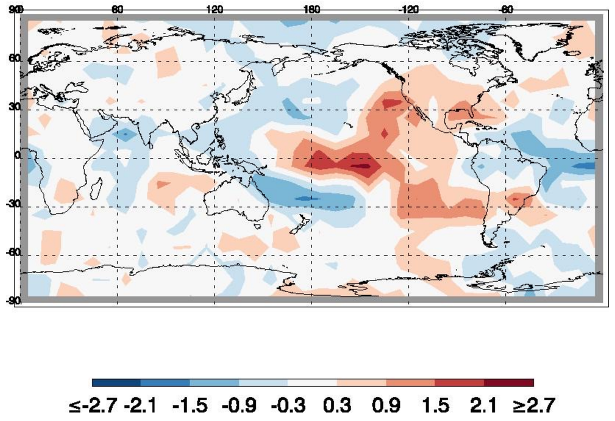
Cloud top boundary trend of high clouds (top at 10-18 km)

Trend (Glo Mean: 0.05±0.05 km/decade)

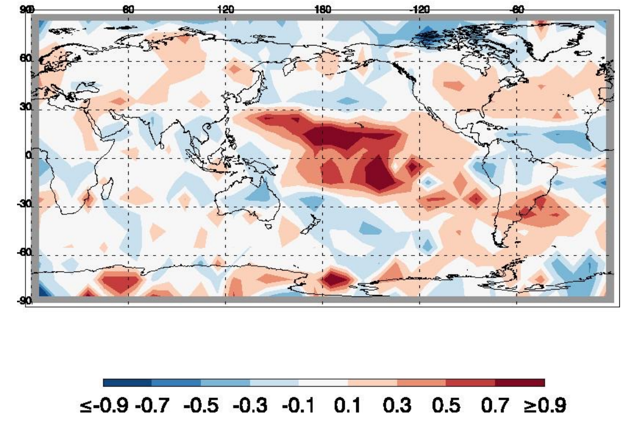


CALCS

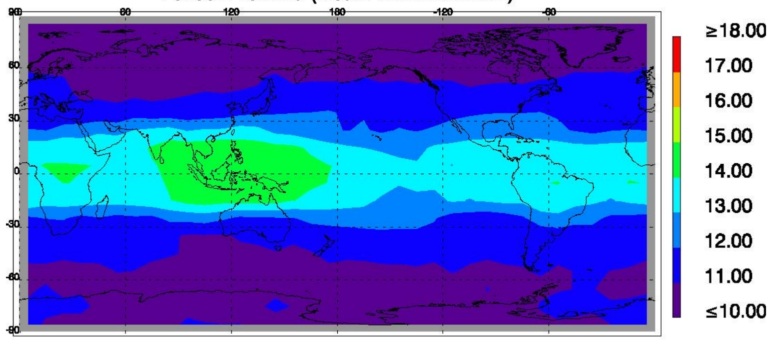
Trend (Glo Mean: 0.03±0.07 km/decade)



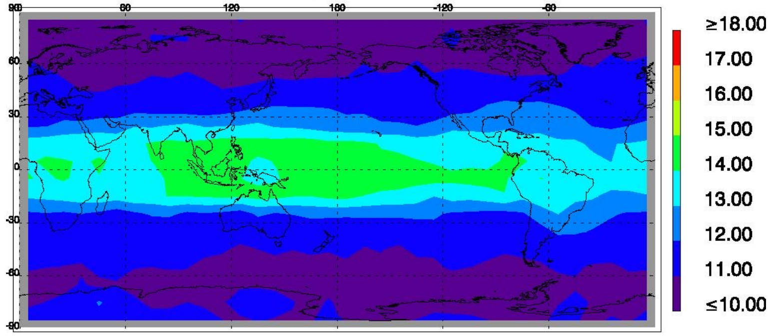
Trend (Glo Mean: 0.07±0.05 km/decade)



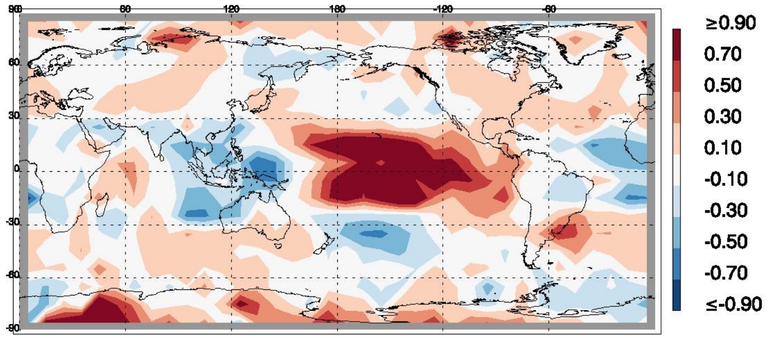
Period1: La Nina (Mean: 12.17±1.22 km)



Period2: El Nino (Mean: 12.27±1.26 km)

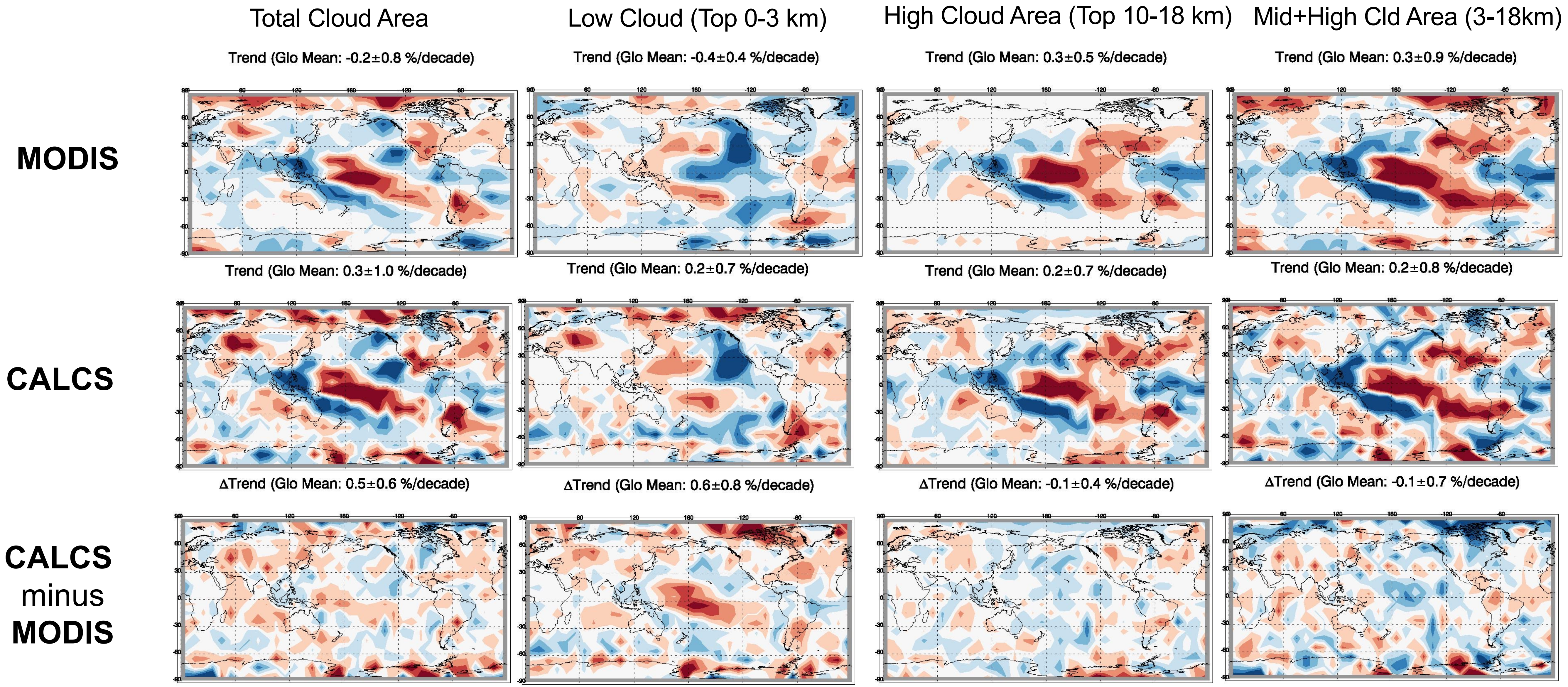


Period2 - Period1 (Mean: 0.10±0.07 km)



- High cloud boundaries are increased over the central Pacific, related to the 2015/16 El Niño event. Both MODIS and CALCS capture consistent cloud top boundary changes.

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



- Good agreement between MODIS and CALCS for mid and high cloud area anomalies between 60°S and 60°N.
- MODIS low cloud trends are larger negative than CALCS anomalies, resulting in negative total cloud trend.
- Both MODIS and CALCS have uncertainties in detecting low clouds below optically thick clouds. Also, further investigation is planned related to CALIPSO single vs non-single lidar shot clouds (next slide).

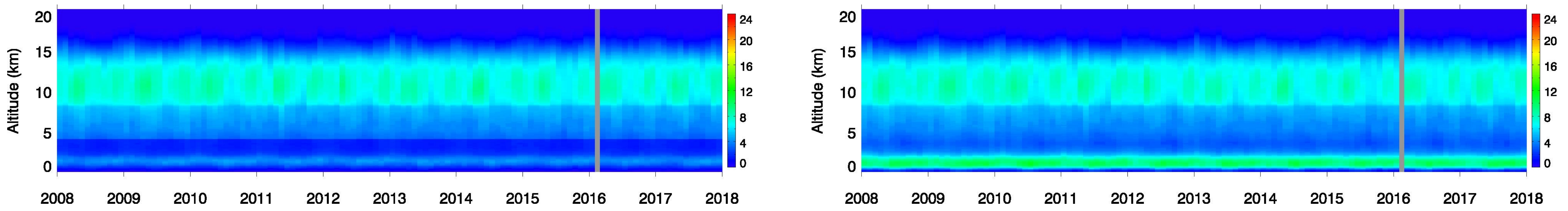
Future Plans: Examining Impact of Filtering CALIPSO Water Clouds Detected from Spatial Averaging

In the present study, we did not include CALIPSO water clouds below 4 km as clouds if these were detected from any spatial averaging (1, 5, 20, or 80 km). In other words, for water clouds below 4 km, clouds detected from a single lidar beam (should have a strong return) are only included. This might dampen the actual low cloud variabilities, especially below 1 km, where CloudSat is not available.

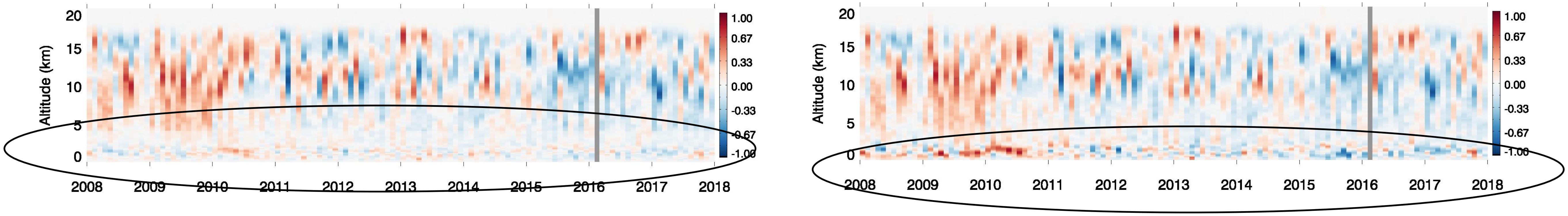
Excluding water clouds detected from spatial averaging (Current study)

Including water clouds detected from spatial averaging

60°S-60°N CALIPSO CALIPSO Cloud Occurrence (%)



60°S-60°N CALIPSO CALIPSO Cloud Occurrence Anomaly (%)



Summary

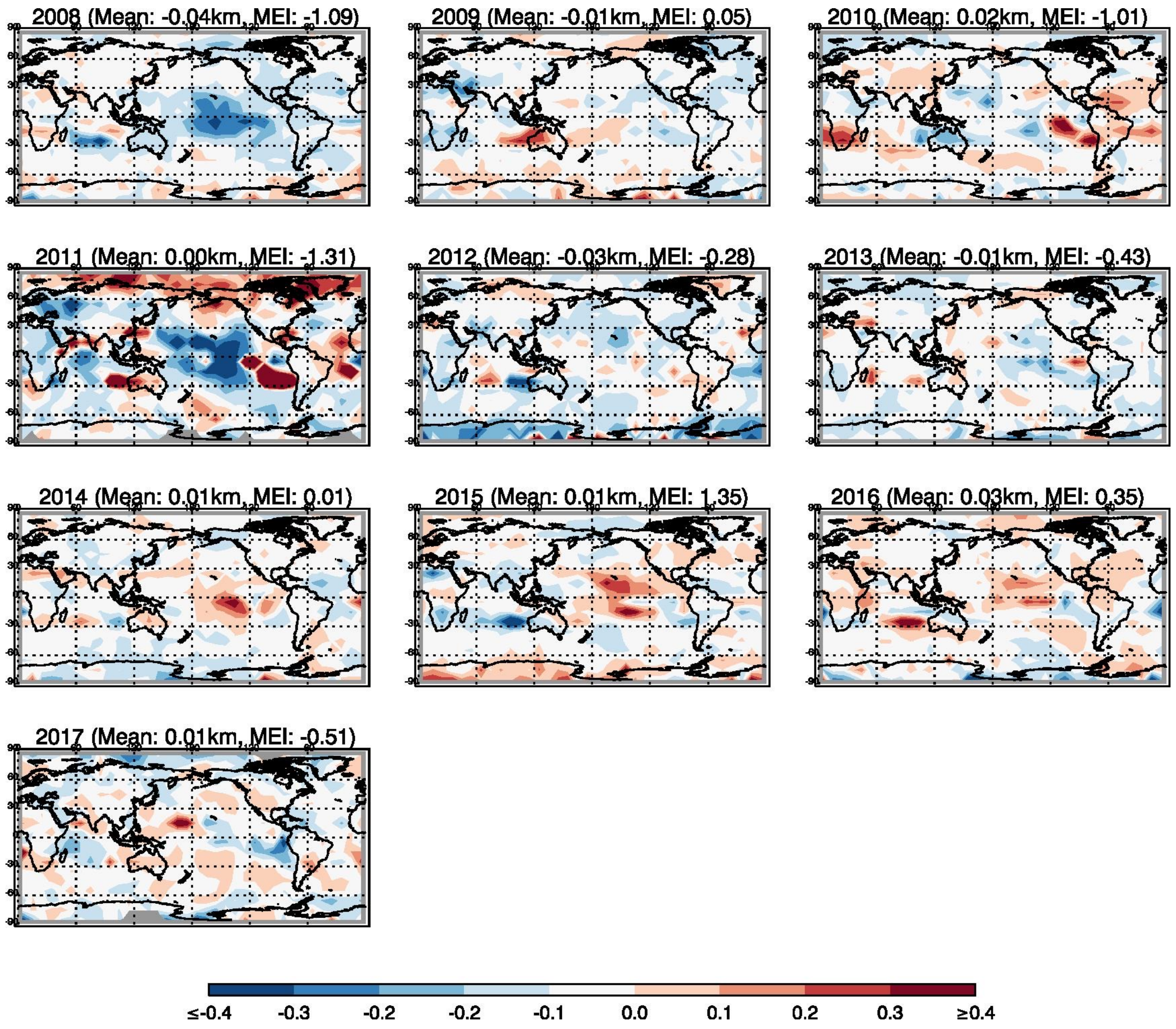
- Several cloud filtering methods to CALIPSO and CloudSat clouds were attempted, in order to make more consistent comparisons and minimize the impact of CloudSat degradation.
- The cloud volume anomalies between MODIS and CALCS are quite consistent between 60°S and 60°N, showing increase of high cloud top boundaries and decrease of mid clouds. These are mostly explained by 2015/16 El Niño event in the later observing period.
- Global distribution of the 10-year cloud trends are quite consistent between MODIS and CALCS.
- MODIS low negative cloud trend is larger than CALCS. This can be explained by 1) limitation of passive sensor of underlying cloud changes 2) limitation of CALIPSO and CloudSat in detecting low clouds below 1 km.
- Polar regions show large deviations between MODIS and CALCS but sampling during daytime is limited, requiring further investigation.

Thank you for your attention!

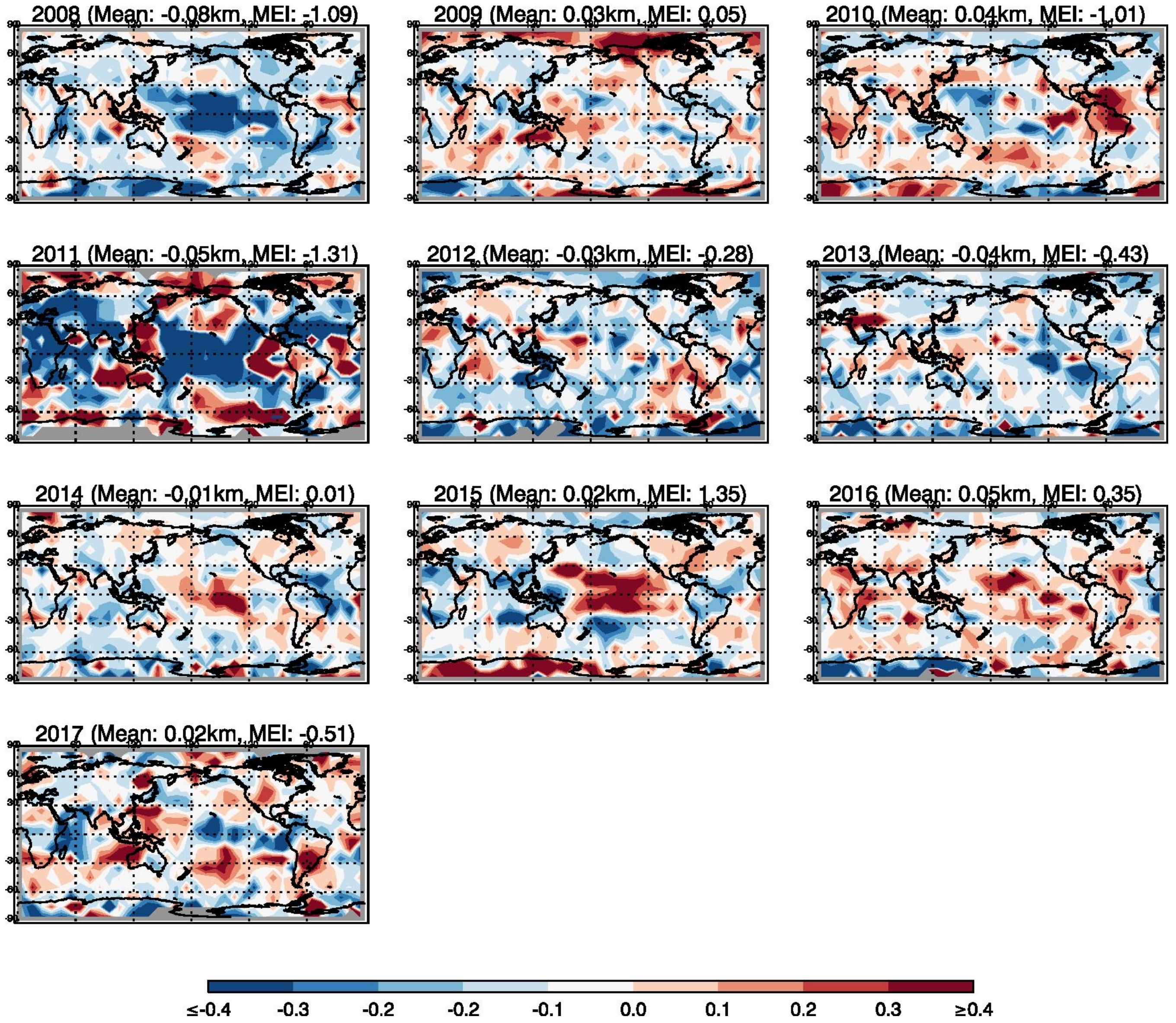
Please contact to seung-hee.ham@nasa.gov if you have any questions.

High Cloud (Top 10-18 km) Top Boundary Anomaly (km)

MODIS

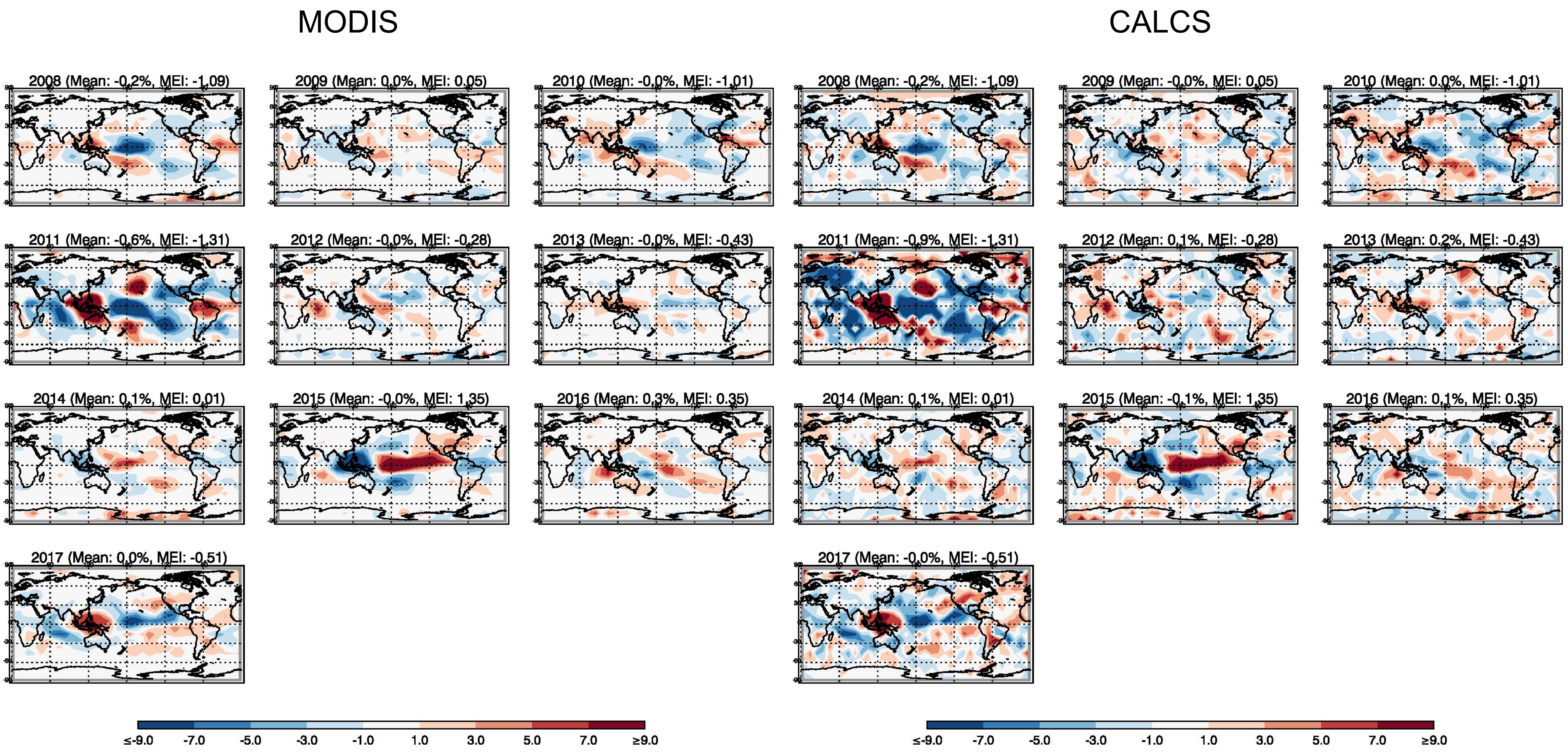


CALCS



Note: There are several missing months in 2011, 2012, and 2017.

High Cloud (Top 10-18 km) Occurrence Anomaly (%)



Note: There are several missing months in 2011, 2012, and 2017.

Kato et al. 2018